1-1-2016

MULTI AGENT SYSTEM APPROACH TO SOLVE DISTRIBUTED ENERGY RESOURCE ALLOCATION PROBLEM TO INCREASE THE STABILITY AND RELIABILITY OF THE DISTRIBUTION SYSTEM

Uditha Sudheera Navaratne
Purdue University

Graduate School Form
30 Updated 12/26/2015

PURDUE UNIVERSITY
GRADUATE SCHOOL
Thesis/Dissertation Acceptance

This is to certify that the thesis/dissertation prepared

By Uditha Sudheera Navaratne

Entitled

MULTI AGENT SYSTEM APPROACH TO SOLVE DISTRIBUTED ENERGY RESOURCE ALLOCATION PROBLEM TO INCREASE THE STABILITY AND RELIABILITY OF THE DISTRIBUTION SYSTEM

For the degree of Doctor of Philosophy

Is approved by the final examining committee:

N. Athula Kulatunga
Chair

Chris Foreman

Raji Sundararajan

Kartik B. Ariyur

To the best of my knowledge and as understood by the student in the Thesis/Dissertation Agreement, Publication Delay, and Certification Disclaimer (Graduate School Form 32), this thesis/dissertation adheres to the provisions of Purdue University's "Policy of Integrity in Research" and the use of copyright material.

Approved by Major Professor(s): N. Athula Kulatunga

Approved by: Kathryne A Newton 11/15/2016

Head of the Departmental Graduate Program Date

MULTI AGENT SYSTEM APPROACH TO SOLVE DISTRIBUTED ENERGY RESOURCE ALLOCATION PROBLEM TO INCREASE THE STABILITY AND RELIABILITY OF THE DISTRIBUTION SYSTEM

A Dissertation

Submitted to the Faculty

of

Purdue University

by

Uditha S. Navaratne

In Partial Fulfillment of the

Requirements for the Degree

of

Doctor of Philosophy

December 2016

Purdue University

West Lafayette, Indiana

ACKNOWLEDGMENTS

First I would like to express sincere gratitude to my advisor, Proessor. N Athula Kulatunga, for the continuous support during my Ph.D study and related research. His patience, motivation, and immense knowledge were invaluable to me. He gave his constant guidance during all of my research and writing for this thesis.

I would also like to thank the rest of my thesis committee for their insightful comments and encouragement.

I have much gratitude for the help and support team of www.meteoblue.com, who provided the vital data that made this thesis possible. The prompt responses from the support team of PowerFactory™were also key . I thank Landis+gyr for providing smart meters and other required assistance in the creation of the smart grid emulator used in providing the evidence to support the thesis.

Last, but not least, I would like to thank my family: my wife, my parents, my brothers and sisters for supporting me spiritually throughout both the writing of this thesis and throughout my life in general.

TABLE OF CONTENTS

Page

LIST OF TABLES

LIST OF FIGURES

Figure Page

ABBREVIATIONS

ACL	Agent Communication Language
AENS	Average Energy Not Supplied
ASAI	Average Service Availability Index
ASIDI	Average System Interruption Duration Index
ASIFI	Average System Interruption Frequency Index
ASUI	Average Service Unavailability Index
CAIDI	Customer Average Interruption Duration Index
CAIFI	Customer Average Interruption Frequency Index
DER	Distributed Energy Resources
DG	Distributed Generation
ENS	Energy Not Supplied
FIPA	Foundation for Intelligent Physical Agents
GIS	Geographical Information System
MAS	Multi Agent Systems
PV	Photovoltaics
RE	Renewable Energy
SAIDI	System Average Interruption Duration Index
SAIFI	System Average Interruption Frequency Index
T&D	Transmission and Distribution

ABSTRACT

Navaratne,Uditha S. Ph.D., Purdue University, December 2016. Multi Agent System Approach to Solve Distributed Energy Resource Allocation Problem to Increase the Stability and Reliability of the Distribution System. Major Professor: N. Athula Kulatunga.

The modern power distribution system differs drastically from the conventional power distribution system. Smart grid and micro-grid technologies make the modern distribution system more complicated. In modern power distribution network two way power flow is possible due to the installation of distributed energy resources compared to the one way power flow from generation to consumer in conventional power distribution system. Utility companies had full control over the conventional power distribution system. With the more and more DERs in placed by privet sectors and some times by individual home owners managing the power distribution system becomes more and more complex. Maintaining the reliability and the stability of the system is becoming a challenge in modern power distribution system. Addition of DERs has significant effect on the reliability of the network.

Planning is critical for reliable and efficient development of the modern distribution system and associated micro-grids. Micro-grid and distribution system planning is computationally complex, time consuming and requires expertise in different disciplines. Multi Agent Systems are widely used to simulate the behavior of different agents collaborating to achieve single or multiple objective functions. Expertise in different areas can be represented by agents with expert knowledge and decision making capabilities.

This thesis investigates the use of MAS to automate the distribution energy resource planning process while increasing the stability and reliability of modern distribution systems and associated micro-grids. Planning process use MAS to find the best location/s, best DER type/s and best capacity/s for a given portion of a distribution system.

CHAPTER 1. INTRODUCTION

Distributed Energy Resources, specifically Renewable Energy base DERs, are gaining attention from the power industry. Recent advancements of technology, consumer demand for clean energy and community interest in energy interdependency increases the utilization of renewable energy resources. Clean energy is not the only advantage of the renewable based DERs. The utilization of DERs provides a way to reach the loads that cannot be easily accessed by the traditional transmission and distribution network. Properly planned and controlled DERs can be used to increase the stability and the reliability of the grid (Ochoa & Harrison, 2011). The DERs should be planned and placed in an optimal manner to obtain maximum usage. Allocation of DERs in distribution network needs to be done in a systematic way to avoid instability of the system (Borges & Falco, 2006). IEEE 1547, Standard for Interconnecting Distributed Resources with Electric Power Systems, provides a set of standards that needs to be carefully followed when interconnecting DERs to medium voltage and low voltage networks.

1.1 Scope

This study examines how multi-agent based simulation techniques can be used to automate the distributed energy resource allocation in distribution systems and in micro-grids.

Generally power grid planning process consists of several steps (Bebic, 2008). They are:

1. Load demand forecasting

2. Reliability evaluation to determine when additional generation is needed

3. Economic analysis to select optimal capacity expansion

According to Qiao (2013), planning of micro-grids and smart grids is a complex process due to:

1. Intermittent renewable energy sources

2. Flexible combination approaches of renewable energy sources

3. Various control strategies, and

4. Different demands for power system reliability

The MAS is promising in handling computationally intensive tasks. Some of the successful implementations using MAS include:

- **eMediator**: eMediator is an electronic commerce sever implemented in java. The server is the first Internet auction which include combinatorial auctions, bidding via graphically drawn price-quantity graphs, and by mobile agents.

- **SARDINE**: SARDINE is an airline flight bidding system. SARDINE (System for Airline Reservations Demonstrating the Integration of Negotiation and Evaluation) use software agents. System consists of buyer agents, airline agents. User can submit simultaneous multiple bids and agents work together to provide the best price to the customer.

Industrial use of MAS can be found in Daimler Chrysler factory of engines in Stuttgart, who implement control system to better occupies its manufacturing equipments(Schild & Bussmann, 2007). Tankers International used an agent based system developed in MAGENTA for their logistic operations (Himoff, Skobelev, & Wooldridge, 2005). Last but not least, US Navy use agent based systems to control heating, ventilation and air conditioning of their ships (Maturana et al., 2004).

Use of Multi Agent Systems in the power industry has been researched and moved to development in last decade (McArthur et al., 2007a). The focus was in diagnosis, condition monitoring, market simulation, power system restoration, control and automation (McArthur et al., 2007a) (McArthur et al., 2007b). However, power system planning was not one of the major considerations. Numerical methods such as: Mixed integer linear programming (MILP), Nonlinear programing (NLP) and Dynamic programming (DPL) was used in order to solve the optimization problem in power system planning. More advance techniques use to solve the optimization problem include heuristic methods such as: Generic algorithms (GA), Practical swamp algorithm (PSA), Evolutionary algorithms (EA), Ant colony System (ACS) and Practical heuristic algorithms (PHA).

This research investigates how agent based systems can be used to overcome the complexities of DER allocation in power system planning. This research also focuses on improving the stability and the reliability of distribution system by introduction of DERs.

Most of the research in distribution system and micro-grid planning using MAS is focused on market oriented simulation as described in chapter 2.5. This study is focused on solving DER placement and capacity allocation in the distribution system planning process, considering the technical aspects using MAS.

1.2 Significance

Micro-grid and DER planning process involve great deal of predictions, forecasting and historical data analysis. Historical data analysis, which is used to find availability of energy resources, is computationally complex. Other computationally expensive tasks in modern distribution system planning include, energy forecasts such as wind and solar energy variations as well as supply and demand prediction (Qiao, 2013).

As discussed in chapter 2.4, agent based simulation helps to properly address the computationally complex tasks. Use of MAS in DER planning will help to reduce the associated computational complexities. MAS can be used to solve multi objective optimization functions associated with the DER planning.

1.3 Research Question

Power industries and research studies currently use different approaches to solve DER allocation. Optimal power flow based DER allocation is the fastest and easiest way to allocate DER. According to Abu-Mouti & El-Hawary (2011) the DG-unit allocation can be interpreted as a mixed integer nonlinear optimization problem. Maximizing the system voltages or minimizing power loss and cost are the typical optimization problems. The solution criteria heavily depend on the application. As more objectives and constraints are considered in the algorithm more data is required which tends to make implementation difficult (Abu-Mouti & El-Hawary, 2011).

Generic algorithms, heuristic approaches, evolutionary programming and particle swarm optimization are some of the tools used in research to simplify the solution to the DER allocation (Abu-Mouti & El-Hawary, 2011; Borges & Falco, 2006; Keane & OMalley, 2005). Some of these techniques have been modified to enhance the performance and most require many parameters to be tuned (Abu-Mouti & El-Hawary, 2011) . This research proposes a novel method to allocate DER in a power distribution system using MAS. MAS is selected due to its real world relation with the problem solving approach using collaboration of different people with expert knowledge and experience.

The key question addressed in this research is:,

Can multi agent based simulation be used to find the optimal DER allocation for a given portion of a power distribution network?

The sub questions include:

1. Can MAS be used to find the best location, optimal capacity and the best type of the DER for a given distribution system?

2. Can MAS be used to find the best placement of the DER to increase the reliability and the stability of a given portion of the electrical distribution system?

   That is to minimize the:

   - Average System Interruption Frequency Index (ASIFI)
   - Average System Interruption Duration Index (ASIDI) and
   - Average Energy Not Supplied (AENS)

1.4 Assumptions

The assumptions for this study include:

- Past weather data and geographical data for the location of interest is readily available.
- Past load profile data for the distribution system under consideration is available for at least one year.
- If no load profile data is available, the customer behavior data collected via survey or any other method is readily available.

1.5 Limitations

The limitations for this study include:

- Limited number of DER types were considered for initial evaluation as proof of concept (wind, solar PV)
- Agents with the simplest form of intelligence were considered for this implementation.
- Only monthly energy consumption was available for the verification of hourly demand variation

1.6 Delimitations

The delimitations for this study include:

- The model is general and can apply for different scenarios.

- The model can be easily upgraded to include both new DERs and objective functions.

1.7 Definitions

Agent: An agent is a computer system that is situated in some environment, and that is capable of autonomous action in this environment in order to meet its design objectives (Wooldridge, 2002).

Capacity factor (net): Capacity factor is the ratio of the net electricity generated, for the time considered, to the energy that could have been generated at continuous full-power operation during the same period (United State Nuclear Regulatory Commission, 2015) .

Distributed Energy Resources: Distributed energy resources are smaller power sources that can be aggregated to provide power necessary to meet regular demand. As the electricity grid continues to modernize, DER such as storage and advanced renewable technologies can help facilitate the transition to a smarter grid (*EPRI — Distributed Energy Resources*, n.d.).

Environment: The environment is the everything external to the agent. Environment can be physical or simulated and should be able to observed or altered by the agent (McArthur et al., 2007a).

Levelized Cost of Energy (LCOE): Levelized Cost of Energy (LCOE) is the constant unit cost (per kWh or MWh) of a payment stream that has the same present value as the total cost of building and operating a generating plant over its life (Black & Veatch, 2010).

Microgrid: A microgrid is a group of interconnected loads and distributed energy resources within clearly defined electrical boundaries that act as a single controllable entity with respect to the grid. A microgrid can connect and disconnect from the grid to enable it to operate in both gridconnected or island-mode (Smith, 2011).

Multi Agent Systems: A multi agent systems is a set of software agents that interact to solve problems that are beyond the individual capacities or knowledge of each individual agent (Potiron, 2013).

Overnight capital cost / Total Overnight Capital (TOC) The Total Overnight Capital (TOC) comprises the Total Plant Cost (TPC) plus all other overnight costs, including owners costs. TOC is an overnight cost, expressed in base-year dollars and as such does not include escalation during construction or interest during construction (Gerdes, Summers, & Wimer, 2011).

The Total Plant Cost (TPC): TPC comprises the Engineering, Procurement, and Construction Cost (EPCC) plus project and process contingencies. TPC is an overnight cost expressed in base-year dollars (Gerdes et al., 2011).

1.8 Summary

This chapter provided the scope, significance, research question, assumptions, limitations, delimitations, definitions, and other background information for the research project. The next chapter provides a review of the literature relevant to power system planing, Multi agent systems, use of Multi agent systems to solve computationally complex problems, current use of MAS in power system applications and modern software tools used in DER planning.

CHAPTER 2. REVIEW OF RELEVANT LITERATURE

This section discusses the traditional and modern power system planning and capacity expansion techniques. State of the art software tools that facilitate the renewable energy planning are also discussed with their pros and cons. The multi agent system architectures are evaluated with their applications in modern power systems.

2.1 Introduction to modern distribution system and micro-grid

Modern distribution systems have evolved rapidly from their primitive past due to availability of smart-grid and micro-grid technologies. According to DOE (2012) the micro-grid definition is adapted from Micro-grid Exchange Group (MEG) and stated as :

> A microgrid is a group of interconnected loads and distributed energy resources within clearly defined electrical boundaries that acts as a single controllable entity with respect to the grid. A microgrid can connect and disconnect from the grid to enable it to operate in both grid-connected or island-mode.

Microgrid Institute (2015) describe four types of micro-grids:

1. Off-grid micro-grids

   Consist of micro-grids that are not connected to the utility grid.

2. Campus micro-grids

Connected to the utility grid but support some level of service in an isolated mode.

3. Community micro-grids

   Connected to the utility and serve multiple customers or services within a community.

4. Nanogrids

   "comprised of the smallest discreet network units with the capability to operate independently. A nanogrid can be defined as a single building or a single energy domain." (Microgrid Institute, 2015)

According to Microgrid Institute (2015) some key driving factors of micro-grids are

- Electricity requirements in remote areas and developing countries
- Demand for reliable, resilient and sustainable service
- Needs of grid optimization, configuration relief and ancillary services by utility companies
- Demand for low cost energy
- Environmental concerns and benefits of using renewable energy

Microgrid Institute (2015) also identify the following as different DERs and technologies available for micro-grids.

- Photovoltaic (PV)
- Wind

- biomass
- small hydro
- Gas or diesel cogeneration / CHP
- Fuel cells and microturbines
- Storage capacity
- Energy management
- Wind, biomass, small hydro

Planning a micro-grid and modern distribution system for renewable energy allocation requires a basic understanding of the traditional power system planning and expansion planning process. Section 2.2 will describe traditional expansion planning, modern distribution system planning and micro-grid planning strategies and criteria.

Section 2.4 gives an introduction to agent based technology that is to be adapted for the planning process. Section 2.5 investigates how agent based systems are used in power system planning and micro-grid planning in today's world.

2.2 Traditional power system, smart grid and micro-grid planning

Before the introduction of micro-grid and smart grid concepts only way of meeting the demand was to expand the transmission and distribution systems and to add new generations at the higher levels. With the introduction of DERs, localized capacity expansion became more popular and cost effective. This section discuss the traditional power system planning approach and how it evolve with the modern power system concepts.

2.2.1 Traditional power system planning and expansion planning

According to Bebic (2008) traditional power system planning consists of;

- Generation planning
- Transmission planning
- Distribution system planning

Generation planning begins with electricity load demand forecasting. Reliability analysis is then performed to evaluate if and when additional generation is needed. Finally, optimal capacity expansions are selected based on the economic consideration (Bebic, 2008). Figure 2.1 shows the least cost generation planning approach used in traditional planning.

2.2.1.1. Traditional power system and key functionality

In a traditional power system, power generation is concentrated at large power stations (Willis, 2004). Transmission and distribution systems are used to transmit the power generated from these stations to the customer. According to the Willis (2004), the required functions of a power delivery systems can be listed as

1. The ability to cover the utility service area in order to reach all the consumers who wish to be connected and purchase power.
2. Ability to meet peak demand of its energy consumers.
3. Provide reliable service to the consumers.
4. Provide the consumers with stable voltage regardless of the changes in load levels.

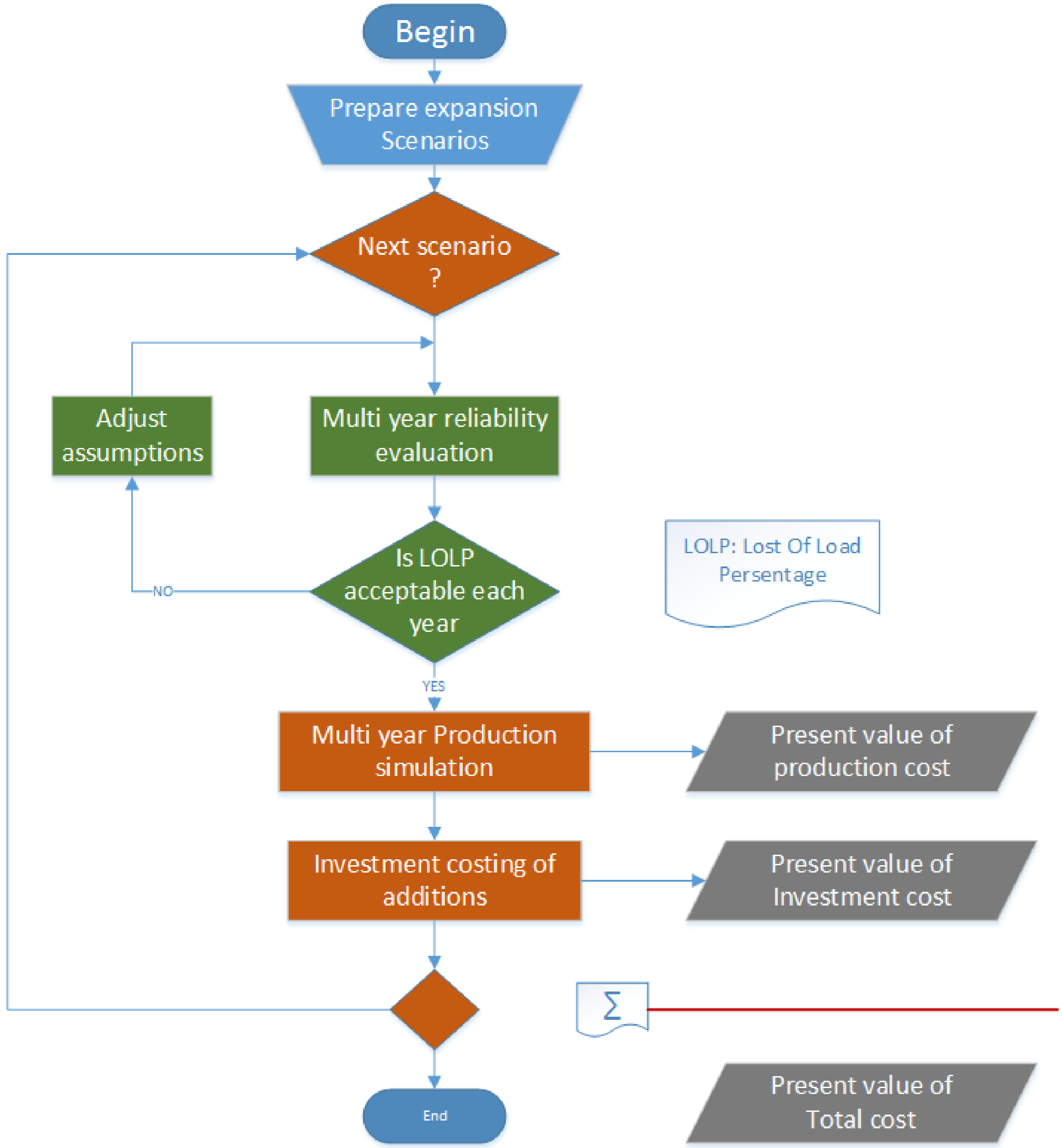


Figure 2.1. Least-cost generation planning (adopted from Stoll 1989) (Bebic, 2008)

The goal is to achieve these functions at the lowest cost possible and in an aesthetically acceptable manner (Willis, 2004).

2.2.1.2. Laws of Transmission and Distribution (T & D)

According to Willis (2004), there exists a set of natural laws that govern the production and transmission of electrical power. These laws listed below dominate the planning and design of T & D.

1. Transmitting power at high voltage is economical. The higher the voltage, the lower the cost per kilowatt to transmit power any distance.

2. The higher the voltage, the greater the capacity and higher the cost of equipments.

3. Power transmission is independent from utilization voltage. Having the lower voltage for a longer distance than necessary increases the power loss, service voltage drop and increase equipment cost.

4. Change the voltage levels is costly. Voltage transformation has nothing to do with power transmission but is a major expense in transmission system.

5. Power is economical to produce in large scale. Although this is true, sometimes distribution generation is economical due to the need of fewer transmission and distribution lines and corresponding equipment.

6. At low voltage levels power must be delivered in relatively small quantities.

2.2.1.3. Planning in the traditional power system (Expansion planning)

According to Dios, Soto, and Conejo (2007) expansion planning is done for ten years with the main focus on final and intermediate year. Expansion planning uses following steps (Dios et al., 2007):

1. Generate multiple scenario for entire planning horizon

   Hundreds of scenarios are generated.

2. Detailed analysis of generated scenarios

   Careful identification of the extreme cases. Each case is associated with a probability of occurrence.

3. Information structuring and index calculation

   Criticality and sensitivity criteria are used to asses the scenarios and reinforcement alternatives (Dios et al., 2007). The characterization of the scenarios follow three types of indices (Dios et al., 2007).

   (a) Extreme values (maxima and minima)

   (b) Probability-weighted RMS values

   (c) Probability-weighted deviations over limits

4. Identification of necessary network reinforcement

   Reinforcements are identified base on the criticality and sensitivity analysis and the planner's experience (Dios et al., 2007). The most important ones are identified based on cost benefit analysis.

5. Decision making

   Charts and graphs are produced based on scenario information and indices to support decision making of higher level managers.

"It is relevant to note that, on average, building a new line requires six years; a new substation four years; a transformer, reactance, or capacitor bank three years; and the repowering of an existing line two years." (Dios et al., 2007)

2.2.2 Modern power system capacity planning

With the vital role of the DERs modern power distribution system planning has changed significantly. Figure 2.2 shows the traditional and emerging techniques use in capacity planning. It can be seen that emerging technology use more and more DER in order to fulfill the capacity requirement in a power system.

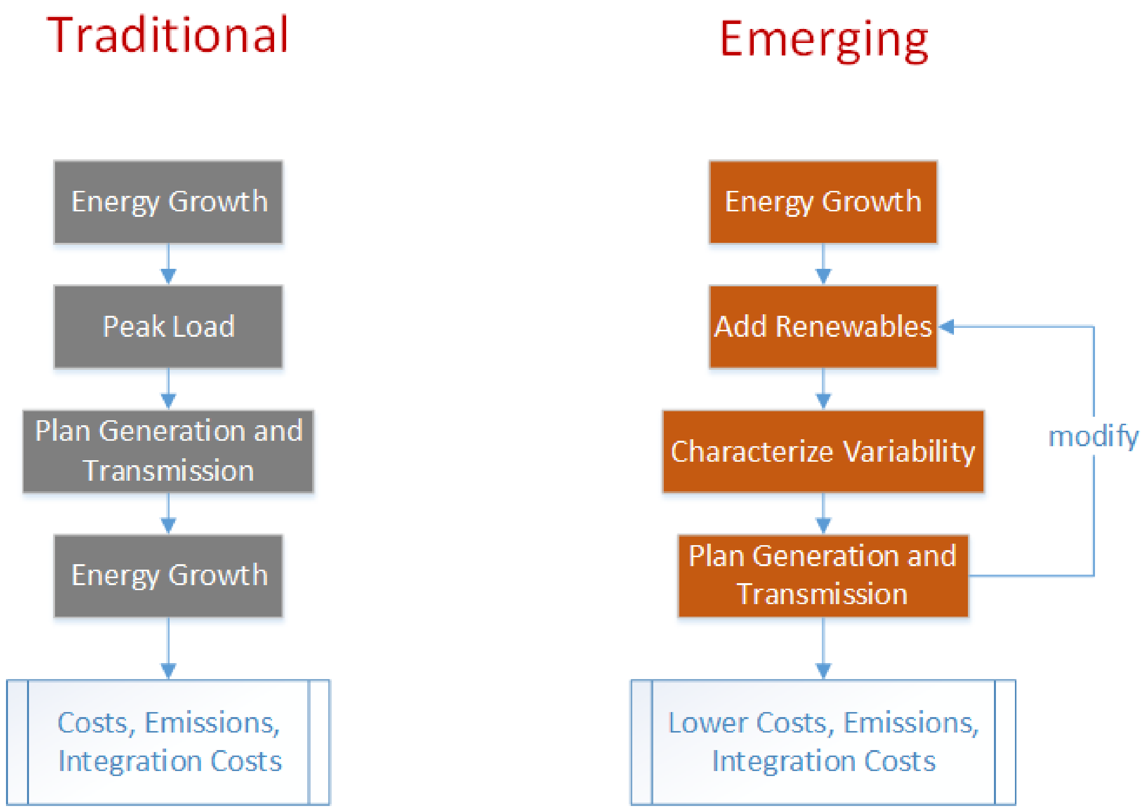


Figure 2.2. Comparison of traditional and emerging practice in power system capacity planning (Bebic, 2008)

Addition to the planning of DER distribution planning consists of finding the optimal locations to place substations and feeders to meet the demand. The major objective functions used in optimization process involves minimizing the following cost functions (Pavlos & Nikos, 2015);

- investment cost
- investment and power lost cost
- investment, lost and reliability cost
- total cost which include investment, lost and reliability and operation and maintenance cost
- total cost minus total revenue

In order to solve the optimization problem Power distribution planning use (Pavlos & Nikos, 2015);

- Numerical methods such as: Mixed integer linear programming (MILP), Nonlinear programming (NLP) and Dynamic programming (DPL)
- Heuristic methods such as: Generic algorithms (GA), Practical swamp algorithm (PSA), Evolutionary algorithms (EA), Ant colony System (ACS) and Practical heuristic algorithms (PHA).

2.2.3 Micro-grid planning

Microgrids can be isolated (standalone) or grid connected. Distributed Generation (DG) and storage in a standalone micro-grid should completely meet the demand. Even a grid connected micro-grid should be able to meet its demand using own DGs and storages completely to support islanding operations without losing any loads. Loads can be categorized as critical and non-critical. Non-critical loads can be disconnected in the islanding operation if DGs and storages don't have adequate energy to meet the demand.

According to Qiao (2013) planning of stand alone micro-grid include planning DG capacity, energy storages and network frame. Factors that make micro-grid planning more complex than the traditional planning include (Qiao, 2013);

1. Inputs from intermittent energy resources
2. Flexible combination approach
3. Various control strategies involved
4. Different demands for power supply reliability

Qiao (2013) also presents micro-grid planning challenges and factors to consider, which are:

1. Uncertainty in DGs

   This creates the requirement for more flexible model and solution algorithms

2. Operational and control objectives

   Various control techniques can be adopted depending on the objective function of the system. For an example, “The optimal objectives of the maximal income and the minimal pollutant emission can be achieved by managing scientifically the different units in a micro-grid system” (Qiao, 2013).

3. Power system reliability

   According to Qiao (2013), “When a stand-alone microgrid system is programmed, the different users’ demands for the power supply reliability should be considered, and then according to the evaluation result of reliability, the planning scheme needs to be modified”

2.2.3.1. Modern smart and micro grid planning criteria

NREL is the one of the leading research institutes conducting research related to renewable energy including micro-grid. NREL and other different research institutions and utilities conduct micro-grid pilot programs. Planning strategies adapted by these institutes in different pilot projects are listed below

1. **NREL Energy Security: Microgrid Planning and Design**

   NREL proposed a concept called Continuously Optimized Reliable Energy (CORE) Microgrids (Giraldez, 2012). NREL focus on the following characteristics

   - Integrates into 24/7 operations
   - Optimizes economics or surety
   - Focuses on fuel diversity
   - Expands/contracts to provide energy for all load coverage spheres
   - Allows for gradual addition of components over time in phased approach

   Economic value, sustainability and energy security are the goals of the NREL approach (Giraldez, 2012). Figure 2.3 shows the NREL micro-grid design process.

   Figure 2.4 shows the key components of the NRELs CORE micro-grid architecture (Giraldez, 2012).

2. **NREL Microgrid Planning and Design MCAS Miramar , US Air Force Academy, and Fort Carson**

   Butt (2011) presented a micro-grid planning and design approach in NREL micro-grid planning and design project at Marine Corps Air Station (MCAS) Miramar. The approach involves 6 steps as shown in figure 2.5.

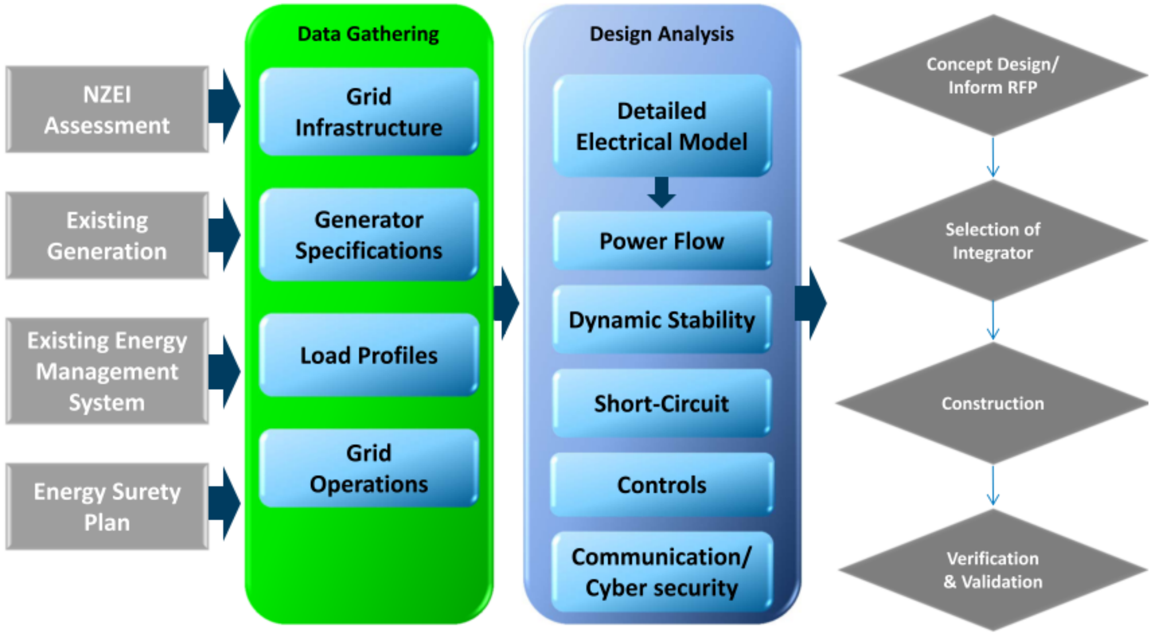


Figure 2.3. NREL micro-grid design process (Giraldez, 2012)

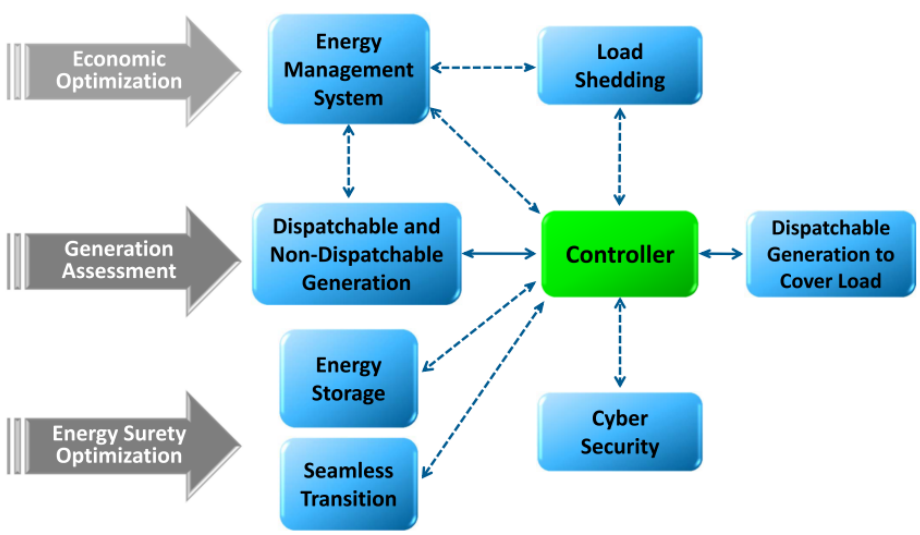


Figure 2.4. Key components of CORE micro-grid (Giraldez, 2012)

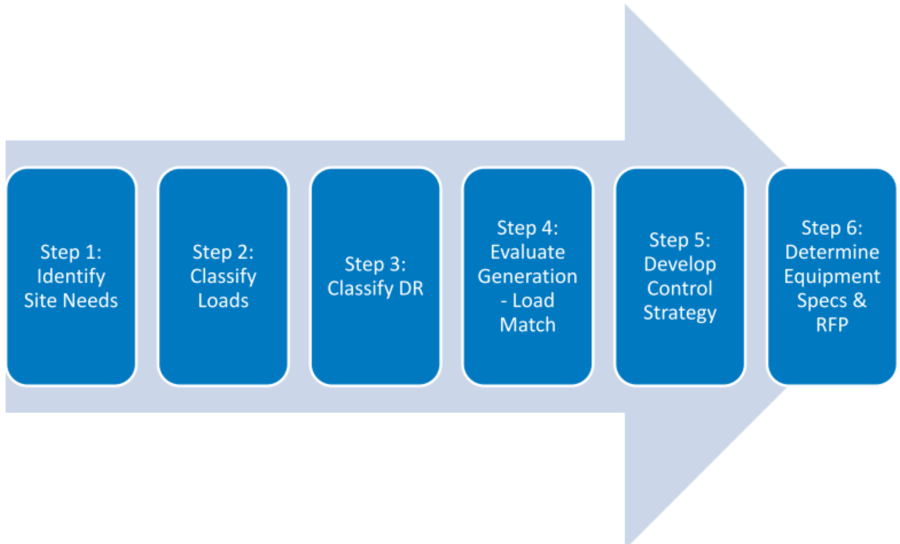


Figure 2.5. NREL micro-grid planning steps as for Robert (Butt, 2011)

The six steps presented by Butt (2011) can be summarized as:

- Step 1: Identify site needs

  This step consists of clarifying the goals of the micro-grid and identifying the factors that impact micro-grid capabilities. Goals of microgrid include identifying the critical facilities in the microgrid which include thresholds and time factors of utility disturbance before transmitting to islanding and identifying the microgrid lifetime (Butt, 2011).

  Factors that impact microgrid capabilities are the mission of the microgrid, geographical layout of the resources and distribution system, available standby generation capacity and control, availability of the resources, load control schemes and utility standards (Butt, 2011).

- Step 2: Classify loads

  According to Butt (2011) loads can be classified using load profiles from AMI, temporary metering or annual data such as daily peaks and seasonal behaviors. The other data that can be used to classify loads include nameplate data, sensitivity to power quality,criticality of loads and flexibility of loads to adjust to the available generation (Butt, 2011).

- Step 3: Classify Distributed Resources

  In this step classification of distributed generations and energy storages are performed. These include classification of existing standby generation characteristics, coverage required for micro-grid, proposed generations, duration requirements, fuel inventory, and distribution storage considerations such as location, capacity, technology and duration (Butt, 2011).

- Step 4: Evaluate Generation/Load match

  This step analyzes the capability of existing/planned generations to meet the peak demand and daily requirements, ability of resources to handle transients disturbance, and the capability of existing generations to handle the variability of the renewable resources (Butt, 2011).

- Step 5: Developing control strategy

  Appropriate control strategies to be developed are studied in this step. These strategies include but are not limited to control strategies for self regulations, control of grid connected/ islanding operations and control of utility interfaces. Other issues to be handled are security concerns, communication requirements, and integration with existing protection schemes (Butt, 2011).

- Step 6: Determine equipment requirements

  This step performs molding and simulations of different scenarios to establish different control parameters, infrastructure modifications, device requirements and additional generation and storage requirements (Butt, 2011).

These six steps provide a guideline to design reliable and efficient micro-grid. However there are many challenges associated with micro-grid planning and design as described by section 2.2.3.2.

2.2.3.2. Challenges faced in modern power system planning

According to Microgrid Institute (2015) some challenges faced in modern power system planning and DER planning, implementation and operation can be listed as

- Government policies and regulations
- Utility tariffs
- Financing
- Risk management
- Interconnection and interoperability
- Resource planning
- System operations
- Technology
- Fuel supply trends

Challenges faced specially during the micro-grid planning process include

- Fluctuation of the output of renewable energy, depending on the time of the day and time of the year (Su, Yuan, & Chow, 2010)
- Time taken for planning due to complexity in micro-grid (Qiao, 2013)

2.3 Tools available for planning

Different software tools are available on the open web and market for renewable energy planning. Most of the softwares are focused on Solar Pv and wind energy. Some are specifically designed for a one type of energy resource and others have the capability of combined simulation. Renewable energy softwares provided by the DNV-GL are examples of single type DER planning tools (DNV-GL, n.d.). The softwares provided by DNV-GL include WindFarmer, TideFarmer, Tide Bladed, Bladed and WaveDyn. The other tools listed below will cover integration of different types of energy resources in DER planning.

2.3.1 Regional Energy Deployment System (ReEDS)

ReDES is a tool developed by NREL's Strategic Energy Analysis Center (SEAC) (NREL, 2014). ReDES is Geographic Information system with multi-regional and multi time period representation capability. ReDES uses linear programming model for capacity expansion planning. The tool is capable of fully incorporating the effect of traditional generations, renewable energy generations and storage systems into the analysis. The principal issues addressed by the software are the

- accessibility and cost of transmission
- accessibility and quality of renewable resources

- variability of wind and solar power
- influence of variability on the reliability of the grid

ReDES facilitate the analysis of different types of energy resources in US market for their impact in different regions. The publications made using ReDES include but not limited to , Considering the role of solar generation under rate-based targets in the EPA's proposed clean power plan by Cole, Mai, Steinberg, and Margolis (2015), meta-analysis of high-penetration renewable energy scenarios by Cochran, Mai, and Bazilian (2014) and renewable electricity futures for the United States by Mai et al. (2014). The disadvantage of the tool is that it is geographically limited to the United States. Analysis is limited ton the transmission system and the energy resources connected to the transmission system.

2.3.2 Stochastic Energy Deployment System (SEDS)

SEDS is another capacity expansion model developed by the NREL. This model utilizes either deterministic or stochastic analysis to analyze the effect of adding renewable energy resources to the US electricity grid. Models use data from five year time frames for the planning process. When operated stochastically, SEDS uses Monte Carlo simulations to make a number of sweeps through the time period. The module captures the dynamics in supply, demand and pricing. SEDS differs from other economy-wide energy models in that it explicitly accounts for uncertainty in technology, markets, and policy (Argonne National Laboratory & Lawrence Berkeley National Laboratoy, 2010). The tool focuses on market and policy based expansion planning within United States.

2.3.3 The HOMER

HOMER micro-grid software provides a detailed chronological simulation and optimization in a model. HOMER can model both the technical and economic factors. For larger systems, HOMER can provide an important overview. HOMER compares the cost and feasibility of different configurations and different technologies so that designers can use more specialized software to model technical performance (*HOMER Energy*, n.d.). Homer supports modeling of conventional and renewable energy technology in an isolated micro-grid environment or in grid connected environment. Homer provides feasibility analysis of a grid build by the user. The user selects the placement and the capacity of each DER. Multiple scenarios can be compared but each has to be modeled separately.

Most of these softwares focus on cost-based analysis. Users have to first decide where to place the DERs or have to use a trial and error method to compare multiple locations. Some of the tools incorporate dynamic behaviors of the loads in their calculations but other power system components like transformers and transmission line behaviors are not incorporated. Once the feasibility analysis is performed, the designer needs to use a power system simulation software to analyze the effect of new DERs on the stability and reliability in the power system . The designer might have to alternate between the planning software and the simulation software to achieve an optimal solution.

The proposed DER planning tool is functional with the power system simulator. DERs are automatically placed in the designed power network during the simulation to analyze the stability and the reliability of the network. The simulator performs multiple sweeps with changing loads which captures the dynamic of the loads and the generation. The position of the DERs are evaluated based on the result of the power flow and the reliability analysis as well as the other factors calculated by the MAS. The Multi Agent System, functioning with the power system simulator, is responsible for analyzing the power flow and reliability. Evaluation of the results generated by the power system simulator paired with the other factors governs achievement of the final objectives.

2.4 Agents and multi-agent systems

According to Shehory and Sturm (2014) "Agents and multi-agent systems (MAS) are a branch of Artificial Intelligence (AI) that attempts to combine AI, distributed systems, and software engineering in a single discipline" (p. 3).Broad description of a agent is a software entity that is acting on behalf of another entity ranging from software to hardware or to human (Shehory & Sturm, 2014). This doesn't imply the presence of any intelligence or autonomy in the agent. More sophisticated agents could have intelligent and/or autonomy built in, making them capable of performing more advanced task with minimum user interaction (Shehory & Sturm, 2014). For example, Belief, Desire, Intention (BDI) agents has software layers specifically designed for intelligence that act based on belief, desire, intention, and goal (Rao & Georgeff, 1995).

According to Shehory and Sturm (2014), the agents ability to collaborate with other agents and non-agent entities is important for performing complex tasks and is known as society (p. 4,5). Collaboration includes negotiation, coordination, resource sharing and understanding other agents. A large system with multiple agents is known as multi-agent system (Shehory & Sturm, 2014).

2.4.1 Properties of an agent

In the development of software agents the central and important properties of an agent can be identified as (Shehory & Sturm, 2014);

1. Autonomy
2. Intelligence
3. Sociality
4. Mobility

2.4.1.1. Autonomy

According to Shehory and Sturm (2014), "Autonomy refers to the ability of an agent to perform unsupervised computation and action and to pursue its goals without being explicitly programmed or instructed for doing so." (p.5). An autonomous agent should have full control of its internal state and its behaviors. The components in the agent's blueprint such as *internal state* and *behavior* support the functions of autonomy (Shehory & Sturm, 2014).

Agents can react to internal and external states and events. These reactions can be *re-active* upon the changes of state or events or *proactive* in which actions are performed in anticipation of events and states. Pro-activeness means a higher level of autonomy (Shehory & Sturm, 2014) .

2.4.1.2. Intelligence

"Agent intelligence may require capabilities such as learning, reasoning, planning, and decision making" (Shehory & Sturm, 2014). These allow an agent to be goal oriented and to have abstract goals. Goals motivate agents to make plans, reason about plans and alternatives, decide rationally upon the best plan, and act accordingly (Shehory & Sturm, 2014).

2.4.1.3. Sociality

In a multi agent environment, an agent should coordinate, collaborate or compete with the other agents to achieve its goals (Shehory & Sturm, 2014). The agent architecture should include sociality-supporting constructs and communication components allowing messages to be passed and processed (Shehory & Sturm, 2014). In order to interact with other agents an agent needs to maintain information about the other agents in the society. This information can include contact details of the agent, capabilities of the agent, and details of past interaction (Shehory & Sturm, 2014). Agents in multi agent systems may also need to include functions like shared plans (Kraus & Grosz, 1996), joint decision making, and multi-agent learning and adaptation (Panait & Luke, 2005) for effective collaboration and decision making.

2.4.1.4. Mobility

Mobility is not a necessity in an agent based system. Agents in multi-agent systems may need mobility to allow changes in its physical location. Mobility can be in different forms. An agent can change its environment by moving from client to server. Also an agent could remain stationary in its device but the device (ex: mobile phone) could move (Shehory & Sturm, 2014).

2.4.2 Agent architectures

Based on the properties of an agent described in section 2.4.1, different architectures can be defined for agent based systems. According to Bellifemine et al. (2007) agent architectures can be divided in to four main groups

1. Logic based architectures

   "Logic-based (symbolic) architectures draw their foundation from traditional knowledge-based systems techniques in which an environment is symbolically represented and manipulated using reasoning mechanisms" (Bellifemine et al., 2007).

   Human knowledge is symbolic, thus this architecture is a close representation of human knowledge. However, translating real world scenario to symbolic representation is complex and time consuming Bellifemine et al. (2007).

2. Reactive architectures

   "Reactive architectures implement decision-making as a direct mapping of situation to action and are based on a stimulus response mechanism triggered by sensor data." (Bellifemine et al., 2007). These agents act fast in dynamic environments and are more simple in design than logic-based systems (Bellifemine et al., 2007). However, these agents can not plan or reason.

3. Belief, Desire, Intention (BDI) architectures

   BDI's origin is in psychology. BDI offers a logical theory based on Belief, Desire and Intention using modal logic (Bellifemine et al., 2007).

   "Many different agent-based systems have been realized that implement BDI (e.g. PRS (Georgeff and Lansky, 1987), JAM (Huber, 1999), JACK (Howden et al., 2001), dMARS (dInverno et al., 1998) and JADEX) with a wide range of applications demonstrating the viability of the model" (Bellifemine et al., 2007).

4. Layered architectures

   This type of architecture supports both reactive and deliberative agent behavior (Bellifemine et al., 2007). Two types of control flows are supported within a layered architecture, namely, horizontal layering (Ferguson, 1992) and vertical layering (Mfiller, Pischel, & Thiel, 1995).

   In horizontal layering each layer act as an agent. The layers are directly connected to input and output. In layered architecture agents only need "n" different types of behaviors. This simplifies the design but makes the actions of the agents inconsistence requiring a mediator to control the action" (Bellifemine et al., 2007).

   Vertical layer architecture deals with some of the issues in horizontal layer architecture as the input and the output in vertical layer architecture are each dealt with at most one layer each (Bellifemine et al., 2007). The vertical layer architecture can be divided in to two types

   (a) One-pass architectures

       Control flow is from the initial layer that gets input to the final layer that generates output

   (b) Two-pass architectures

       Data flow is from initial to final layer and then control flows back down. InteRRaP is an example of vertically two - pass agent architecture (Muller & Pischel, 1993)

   Figure 2.6(a) shows the horizontal layered architecture. Figure 2.6(b) and 2.6(c) show the two different types of vertical layered architecture.

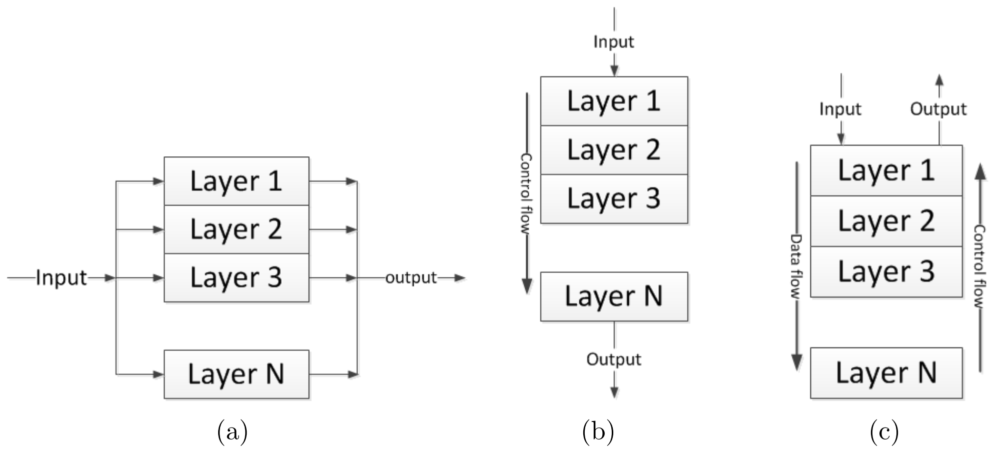


Figure 2.6. Layered architectures: (a) horizontal layered, (b) one-pass vertical layered, (c) two-pass vertical layered (Bellifemine et al., 2007)

2.5 Agent based approach in power system expansion planning

Multi Agent Systems are used in many applications around the world in different fields (Bellifemine et al., 2007). According to McArthur et al. (2007a) MAS are used in many different areas of electrical power engineering such as diagnostics , condition monitoring, power system restoration, market simulation, network control and automation.

Gnansounou, Dong, Pierre, and Quintero (2004) use MAS to simulate market oriented power generation expansion planning. Contreras and Wu (2000) present a kernel oriented algorithm for transmission expansion planning. This paper focuses on multi-agent settings and cooperative game theory base approaches for transmission expansion planning.

Electrical grid planning through scenario building proposed by Alfaro and Miller (2011) suggest a planning process using agent based modeling for developing countries. The conceptual model developed uses four different agents: governments, rural centers, urban centers, and organizations. This model considers PV, small wind, and micro hydro as available RE sources (Alfaro & Miller, 2011). The model is based on the political and social aspects of planning.

Micro-grid expansion planning by He and Sharma (2013) use bi-layer (operational layer and investment layer) agent based model. This paper focuses on market oriented simulation for expansion planning.

Oliveira, Pinto, Praca, Vale, and Morais (2013), Araneda and Ríos (2005), Oyarzabal, Jimeno, Ruela, Engler, and Hardt (2005) and Ferreira, Leitão, and Vrba (2014) present agent based systems for micro-grid management. Prakash, Rajasekaran, and Veerappan (2012), Elamine (2014), Wang, Yang, and Wang (2011) and Ding and Luo (2014) present agent based systems for micro-grid and smart grid controls.

2.6 Summary

This chapter provided a review of the literature relevant to microgrid planning, agent based systems and the use of multi agent simulation for microgrid planning. This section also discussed state of the art software designed to plan DERs in a modern power system including microgrids. It showed that MAS has been used by several researchers for microgrid planning but the main focus was in market based simulation. Research on placement of the DER in a micro-grid or a given section of a power system using MAS to increase reliability has not been conducted and is identified as a gap in the research area. This research will focus on using MAS to micro-grid planning in resource allocation perspective (i.e.how to properly place DER in a given micro-grid location) The next chapter provides the framework and methodology used in the research project.

CHAPTER 3. METHODOLOGY

This chapter provides the framework and methodology to be used in the research study.

3.1 Study Design

This study focused on automating the renewable energy allocation in a selected micro-grid, smart grid or in a part of the traditional distribution system.

Implementation was planned in four approaches and implemented one of those four.

Approach one utilized the following softwares:

- PowerFactory^{TM} to model the grid
- Python to create MAS and to integrate MAS with PowerFactory^{TM}.

Softwares planned to use with approach two are:

- MATLAB^{TM} simulink to model the grid
- Java Agent Development Environment (JADE) to develop MAS.
- MATLAB^{TM} to integrate simulink and the JADE

Approach three considered using:

- MATLAB^{TM} R2015a to model the grid
- Magentix 2 to create Multi Agent System

- MATLAB^{TM} "call java libraries" to call "Magentix 2" agents from MATLAB^{TM}

The fourth approach considered:

- PowerFactory^{TM} to model the grid.
- Repast Simphony to model the MAS
- Python to integrate Repast Simphony and the PowerFactory^{TM}.

Advantages, disadvantages and challenges in these four approaches are studied and discussed in section 3.1.1.

3.1.1 Advantages/Disadvantages and challenges in four approaches

3.1.1.1. Approach I

This approach uses PowerFactory^{TM} to model and simulate the micro-grid. PowerFactory^{TM}is a commercial software designed to model and simulate power systems. PowerFactory^{TM} is capable of performing power flow analysis, fault analysis and many other types of analysis required in power system studies (DIgSILENT, 2014). PowerFactory^{TM} 15.1 onward supports Python as an integrated programming language. Python is an evolving programming language with many libraries to perform different tasks. SPADE (*Smart Python multi-Agent Development Environment*) is the python environment for MAS implementation (SPADE, n.d.). SPADE 2.2.1 is considered for approach I.

- Advantages

1. PowerFactory is an advanced software specifically created for power system analysis.
2. Python is an object oriented programming language with an open source license
3. Python is rapidly evolving and built-in libraries are available to simulate Neural Networks, Artificial Intelligence and Multi Agent systems .

- Challenges

1. SPADE 2.2.1 is designed for linux base systems and windows compatibility problems are not 100% resolved.

3.1.1.2. Approach II

Aproach II was planned with the intent of useing Matlab^{TM} to model the electrical grid. SimPowerSystem toolbox in Matlab Simulink can be used to model the electrical network. Agent based system can be developed using Java Agent Development Environment (JADE). Communication between JADE and Matlab needs to be developed in order to support information flow.

- Advantages

1. JADE is well tested and widely used tool for MAS developments.
2. Matlab supports power system simulations via SimPowerSystem and additional functionality can be implemented using other toolboxes and libraries available.

- Challenges

1. Interface between Matlab and JADE is not well defined.
   MACSimJX is a software which enable Matlab to operate with JADE (University of York, 2009) . The software is developed and tested with Matlab 2009/2010 and is not fully compatible with the newer version of Matlab. No support is available for newer Matlab versions.

3.1.1.3. Approach III

Aproach III also planned to use Matlab^{TM} to model the electrical grid. The SimPowerSystem toolbox in Matlab Simulink can be used to model the electrical network. MAS was planned to be developed using "Magentix 2", a java based agent development platform. Matlab 2015a "java call libraries" was planned to use in order to exchange messages and data between magentix agents.

- Advantages

  1. Magentix 2 is java based well tested and widely used environment for MAS developments. Magentix uses FIPA-ACL messages to communicate between agents.
  2. Matlab supports power system simulation via SimPowerSystem and additional functionality can be implemented using varying toolboxes and libraries available.
  3. Matlab R2015a supports easy call and message exchange with java classes using Matlab's java call libraries.

3.1.1.4. Approach IV

Approach IV was designed to use the PowerFactory to model the grid. As discussed in approach I, PowerFactory is a well tested and commercially used power system simulator. Repast Simphony, a java based MAS development tool was planned to use for modeling of the multi agent system. The python program can be used to integrate PowerFactory and Repast Simphony.

- Advantages

    1. PowerFactory is a well tested power system simulator
    2. PowerFactory supports integrated programming and handles its objects using Python
    3. Repast Simphony is an open source MAS development tool based on java and can integrate different functionalities via java packages.
    4. Python supports two way communication with java via Py4j, which can be used to link agents in Repast with the objects and functions in PowerFactory

Out of these four, approach IV was selected for the implementation after carefully evaluating the pros and cons of each. PowerFactory was used to model the power system and Repast Simphony was used to model the MAS. Python was used as a mediator to facilitate the communication between PowerFactory and the Repast Simphony.

Following subsections will describe the step by step procedure taken to implement the DER planning tool. Section 4 will present the results and analysis.

3.1.2 Power system modeling

The first step in the planning was to model the power network under consideration. The network needed to be modeled in detail including switches and breakers in the system to facilitate the reliability analysis, so that the best results from the DER allocation tool could be obtained. The power network was modeled using a commercially available power system simulator known as PowerFactory. The DER allocation tool was tested with part of a Brazilian power distribution network. The power network in Estrela da Ilha, a farming community in a city called Ilha Solteira was modeled. The community suffers from frequent power outages and bad power quality problems and requires a permanent and reliable solution to their problems. The DER allocation tool was developed for use in any power distributed system with the specific requirements of the Estrela da Ilha system in mind.

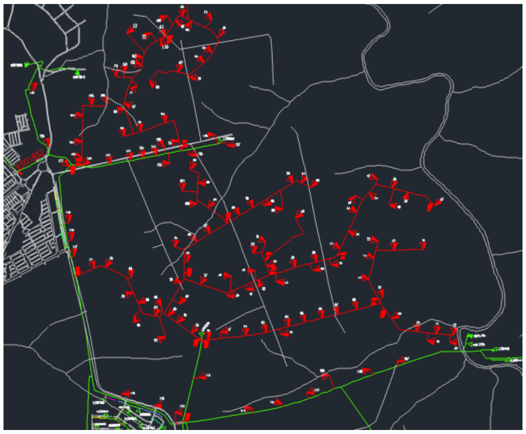
The Estrela da Ilha power network consists of approximately 120 load points or lots. Most of the lots consists of farm land with a small house and storage building. Figure 3.1 shows the location of the Estrela da Ilha site with respect to the Ilha Solteira City.

Figure 3.1. Estrela da Ilha site with respect to Ilha Solteira city

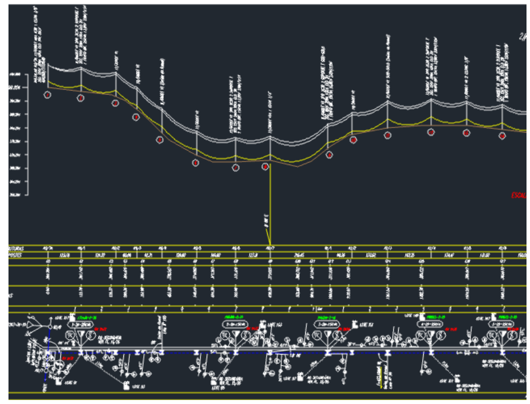
A 13.8 kV 2 phase electricity distribution network supplies power to individual lots in Estrela da Ilha via 13.8 kV (230/115 V) step down transformers. These transformers typically have a power rating of 15kVA or 25 kVA. Data for Estrela da Ilha was provided by ELEKTRO, the electric utility in the area, as shown in Figure 3.2. AutoCAD drawings in Figure 3.2(a) shows the complete Estrela da Ilha power network with all the transformer locations. Figure 3.2(b) shows the part of the detailed diagrams with the description of pole types, cable types, transformers and load points in the network and corresponding connections including distances. Figure 3.2(c) and Figure 3.2(d) show loads connected to transformers and details of associated cable types and lengths, transformer parameters, and corresponding load values. The load points provide their maximum kVA demand and corresponding power factor. Load curves and information which are necessary for dynamic simulation was not provided in ELEKTRO data set. The enlarged diagrams are shown in F

DigSILENT PowerFactory (DIgSILENT, 2014) was used to model the Estrela da Ilha power system. DigSILENT PowerFactory is a commercially available power system simulation software with more sophisticated functionalities. The proven advantages of the PowerFactory software are its overall functional integration, its applicability to the modeling of generation, transmission, distribution and industrial grids, and the analysis of these grid's interactions (DIgSILENT, 2014). PowerFactory specific programming language known as DigSILENT Programming Language (DPL) and the new support for Python programming language (PowerFactroy version 15.1 onwards) provide more flexibility to the modeling and analysis

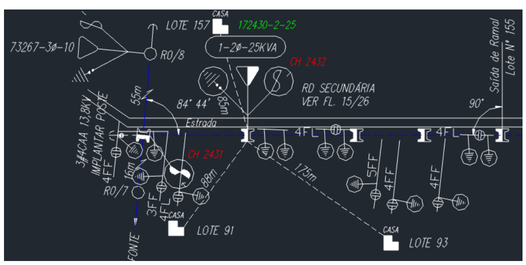
PowerFactory has a global library that stores different power system components such as cable types, transformers, relays, and induction machines with



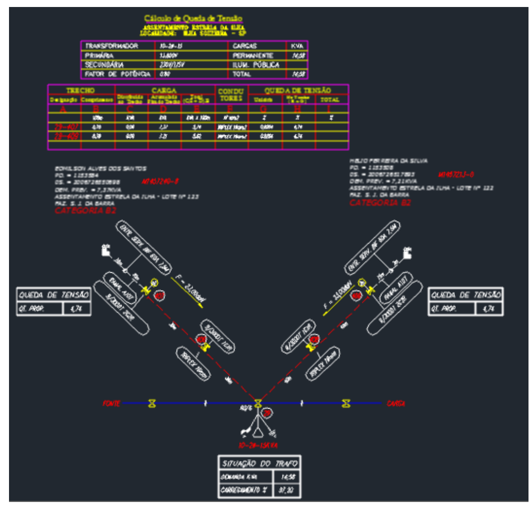
(a) Complete electrical network



(b) Example distribution line with connected components



(c) Example connection of load points



(d) Example load point details

Figure 3.2. Estrela da Ilha electrical diagrams as AutoCAD drownings (*ELEKTRO*, n.d.).

specific parameters. Users can customize these components and adapt them to match the components in the modelling system and can also be stored in local project libraries. The component used in Estrela da Ilha network is listed in Table 3.1 with basic parameters.

Each element in the modeled network inherits and stores data from their corresponding component type. Every line in the network inherits common

Table 3.1
Estrela da Ilha power network component types and basic parameters

Component type	Description	Basic parameters	Parameter value
Cable Types	2/13.8kV ACSR SWAN 4AWG	Rated Voltage	13.8 kV
		Rated Current	0.14 kA
		Nominal Frequency	60 Hz
		1,2 sequence Resistance at 20 C	1.35 Ohm/km
		Zero sequence Resistance at 20 C	4.05 Ohm/km
Transformer Types	0.015 MVA 13.8/0.23kV WEG	Rated Power	0.015 MVA
		Phase Technology	Single
		Nominal frequency	60 Hz
		Copper loss	0.3kW
		Short circuit voltage uk	1%
		No load current	0.7 %
		No load loss	0.2 kW
Transformer Types	0.025 MVA 13.8/0.23kV WEG	Rated Power	0.025 MVA
		Phase Technology	Single
		Nominal frequency	60 Hz
		Copper loss	0.57kW
		Short circuit voltage uk	3.5 %
		No load current	0.7 %
		No load loss	0.2 kW
Busbar Type	Bar-13.8kV	Nominal voltage	13.8 kV
Terminal Types	13.8 kV Terminal	Nominal Voltage	13.8 kV
		Target voltage	1 p.u.
		Delta V max	5 %
		Max Voltage	1.1 p.u.
		Min Voltage	0.9 p.u.
Terminal Types	0.23 kV Terminal	Nominal Voltage	0.23 kV
		Target voltage	1 p.u.
		Delta V max	5 %
		Delta V min	-5 %
		Max Voltage	1.1 p.u.
		Min Voltage	0.9 p.u.

parameters from line type. All transformers in the network inherit parameters from relevant transformer types. Each component acquires and retains all the parameters.

3.1.2.1. Modeling of the test power network in PowerFactory

This section describes the modeling of individual component types in the power network and how to combine them to build the complete power system under consideration.

3.1.2.1.1. External Grid

The starting point of the power network is the external grid. The external connections to the power network of interest is modeled as the external grid. In this way we don't need to know the exact details of the power grid that is external to the Estrela da Ilha grid. Only the Estrela da Ilha power network was modeled in detail. Figure 3.3 shows the configuration of the external grid in PowerFactory. The grid was modeled as slack bus which balances the active and reactive power of the system.

3.1.2.1.2. Distribution lines

Figure 3.4 shows the example of distribution line modeling in the PowerFactory. Figure 3.4(a) shows a section of a distribution line in the Estrela da Ilha power network. Figure 3.4(b) shows the configurations associated with the distribution line segment. Each distribution line in the oneline diagram inherits its parameter from a line type defined in the project. Figure 3.4(c) shows the basic configuration of the line type associated with the distribution line segment shown in Figure 3.4(a).

3.1.2.1.3. Transformers

All the transformers in the modeled grid are 13.8kV/230V. Figure 3.5(a), Figure 3.5(b) and Figure 3.5(c) shows the example of a transformer in an one line diagram, its configuration and its type definition in the PowerFactory.

3.1.2.1.4. Loads

Each load in the network represent a lot in the Estrela da Ilha site. All the loads in the networks were modeled as low voltage loads with nominal line to line voltage of 230 V. Figure 3.6(a) shows the load points in the PowerFactory one line diagram. Figure 3.6(b) shows the sample configuration of load parameters. These load parameters will automatically update via the Python program during the simulation to represent the time varying load characteristics.

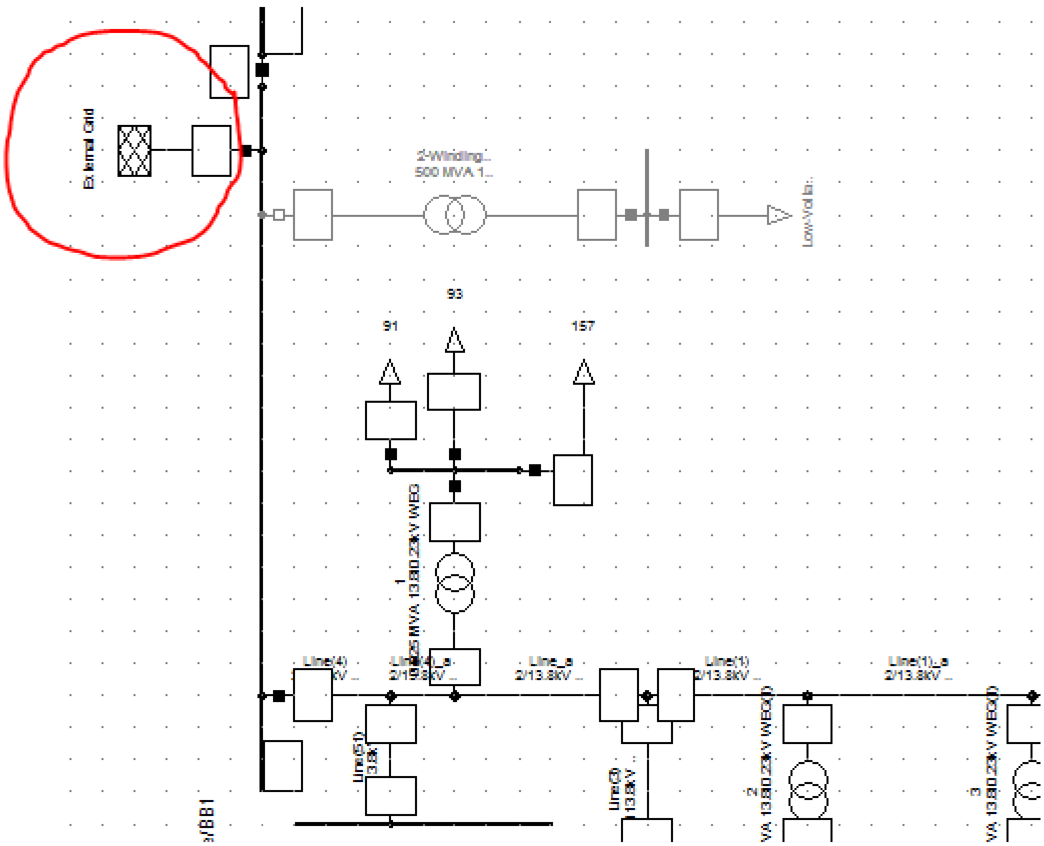
3.1.2.1.5. Complete power system

The complete distribution network model was created by interconnecting many of the components described in the previous section to match the specification provided by the ELEKTRO. Figure 3.7 shows the complete model of the Estrela da Ilha distribution network.

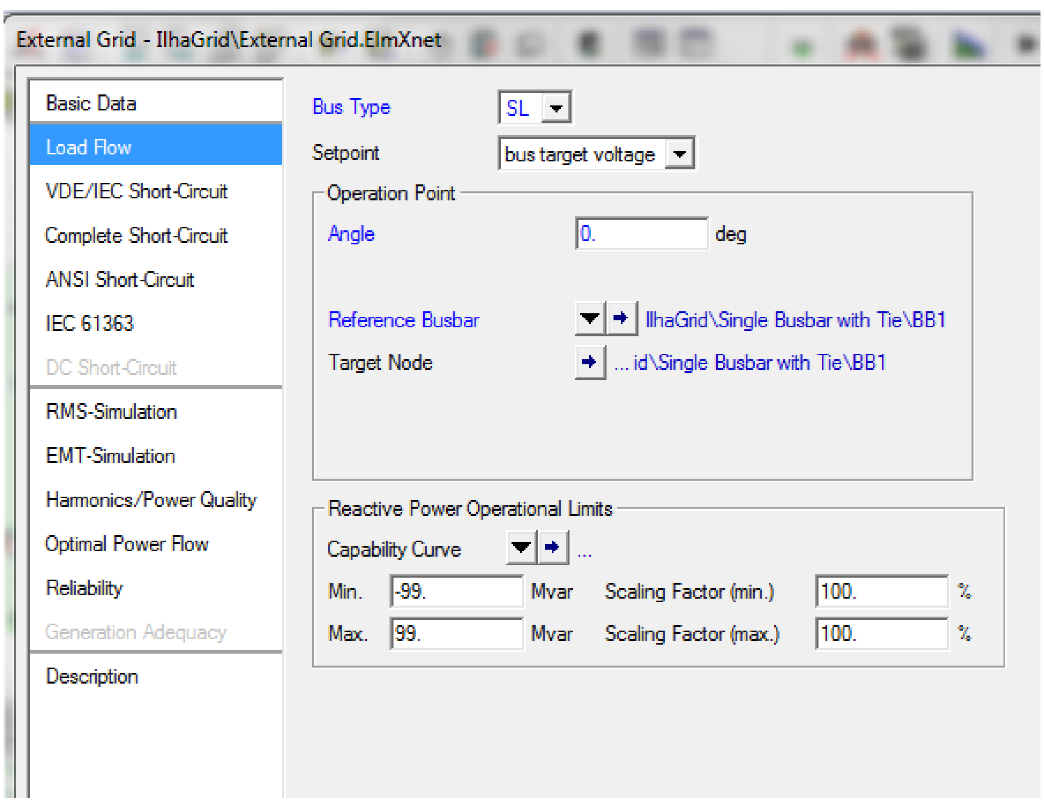
Power flow and reliability analysis tests were performed on the distribution network.The agent based model describe in section 3.2 will also use the results from these two analysis as feedback to the agent system. The following two sections will explain the details of power flow analysis and reliability analysis.

3.1.2.1.6. Powerflow analysis

In PowerFactory power flow analysis can be performed using either graphical user interface or codes written by using DPL or Python. This project uses python as the main programming language to interact with PowerFactory. Figure 3.8 shows the basic configuration dialog of the power flow analysis in the PowerFactory. The PowerFactory dialog for power flow provides various configurations for active power control, Load/Generation scaling, and low voltage analysis among other things.

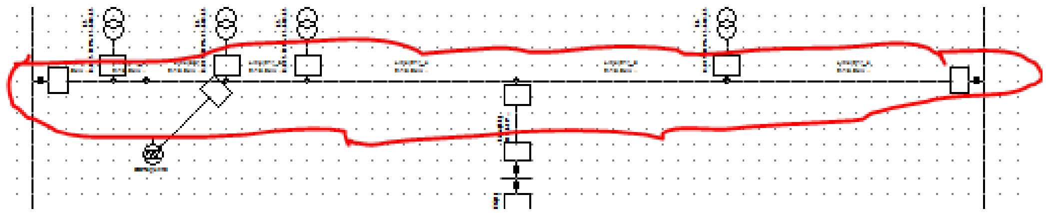


(a) Oneline diagram of the external grid in PowerFactory

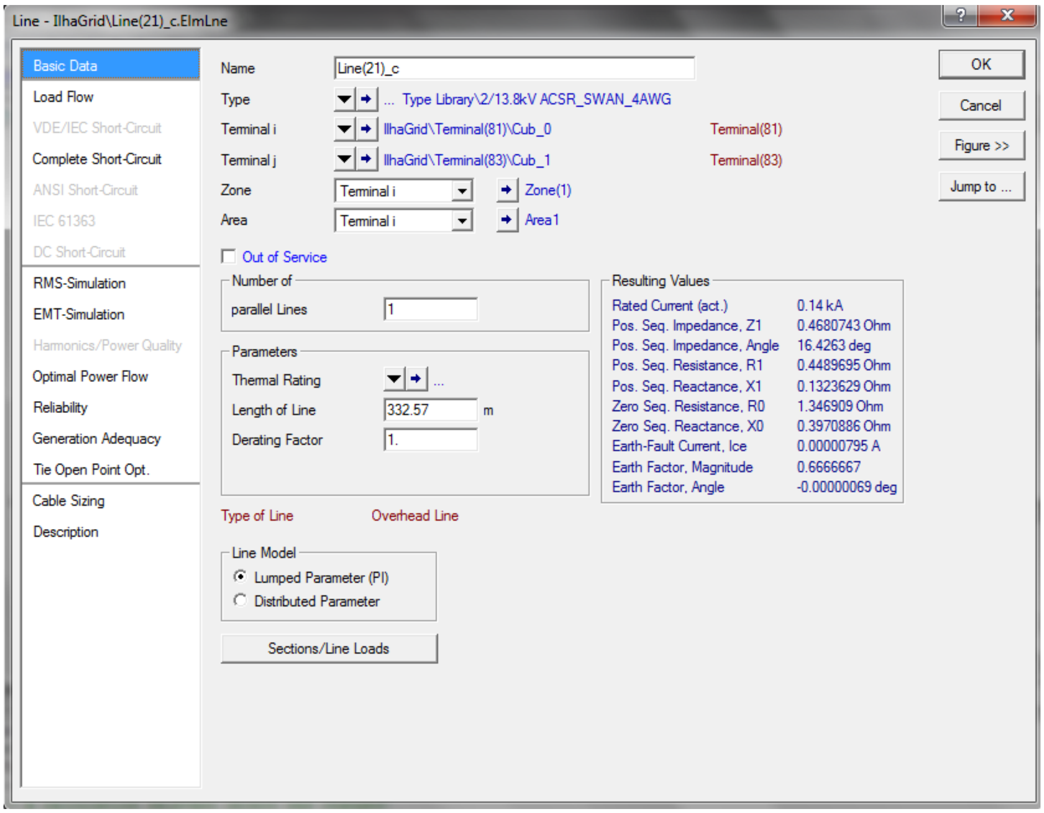


(b) External grid configuration in PowerFactory

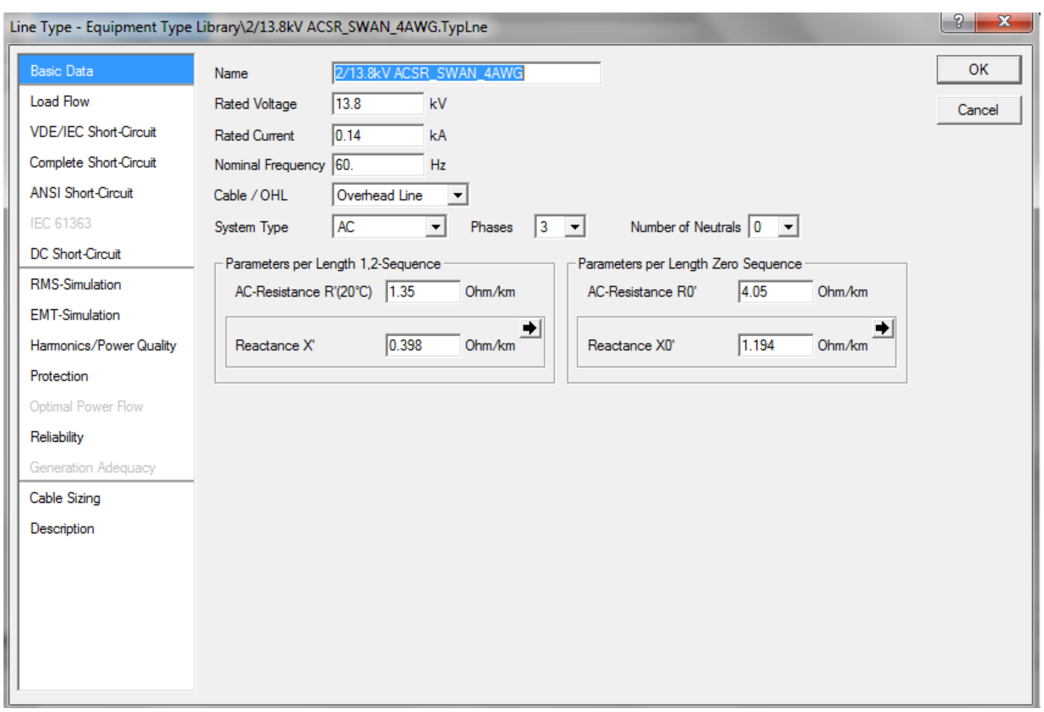
Figure 3.3. External grid in PowerFactory



(a) Distribution line in PowerFactory oneline diagrem

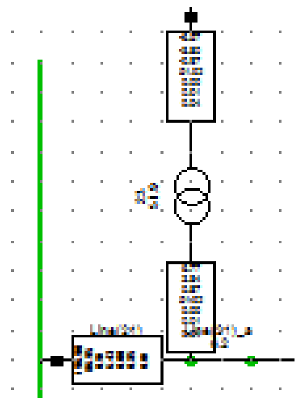


(b) Distribution line configuration in PowerFactory

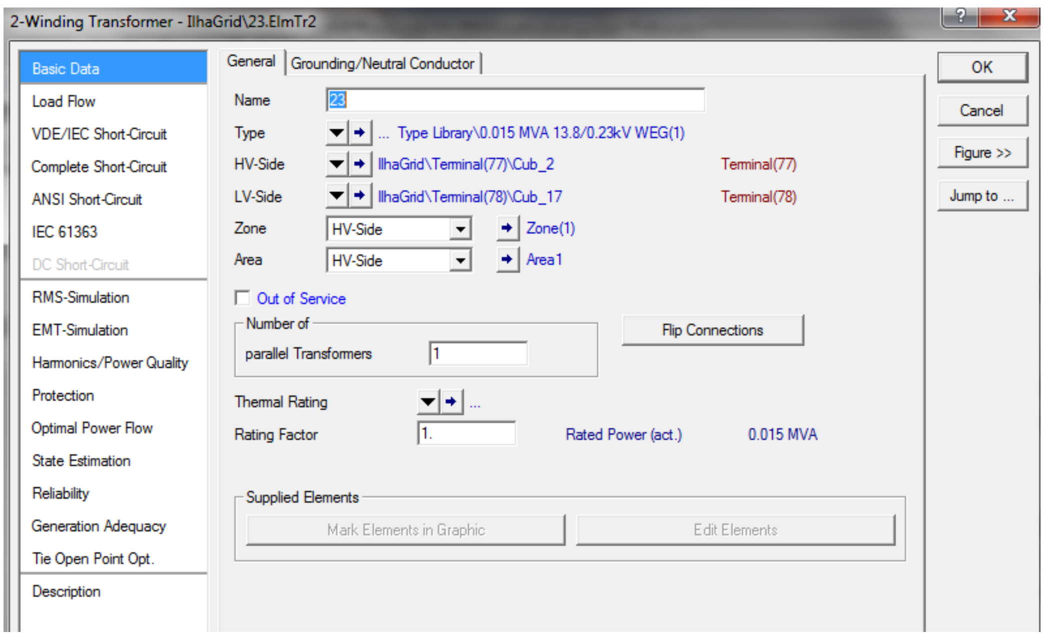


(c) Line type configuration in PowerFactory

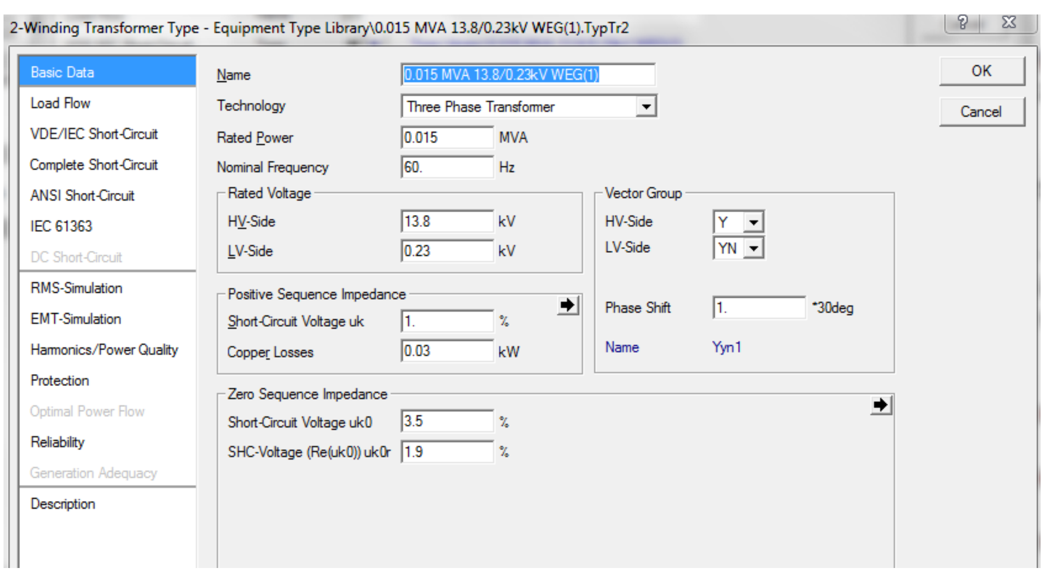
Figure 3.4. Distribution line in PowerFactory



(a) Distribution transformer in PowerFactory one line diagram

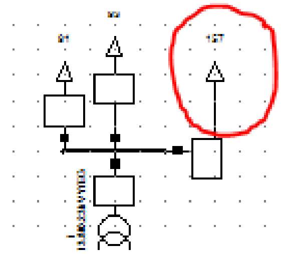


(b) Distribution transformer configuration in PowerFactory

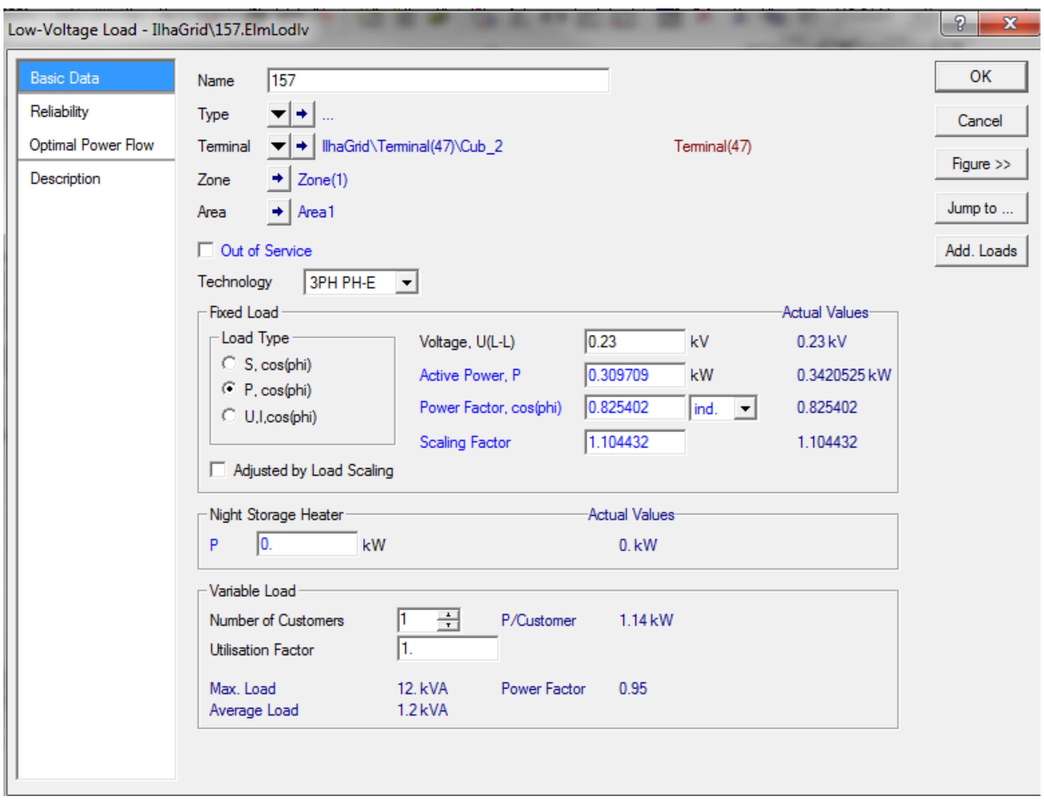


(c) Transformer configuration in PowerFactory

Figure 3.5. Distribution line in PowerFactory



(a) Low voltage load in PowerFactory one line diagram



(b) Low voltage load configuration in PowerFactory

Figure 3.6. Low voltage load in PowerFactory

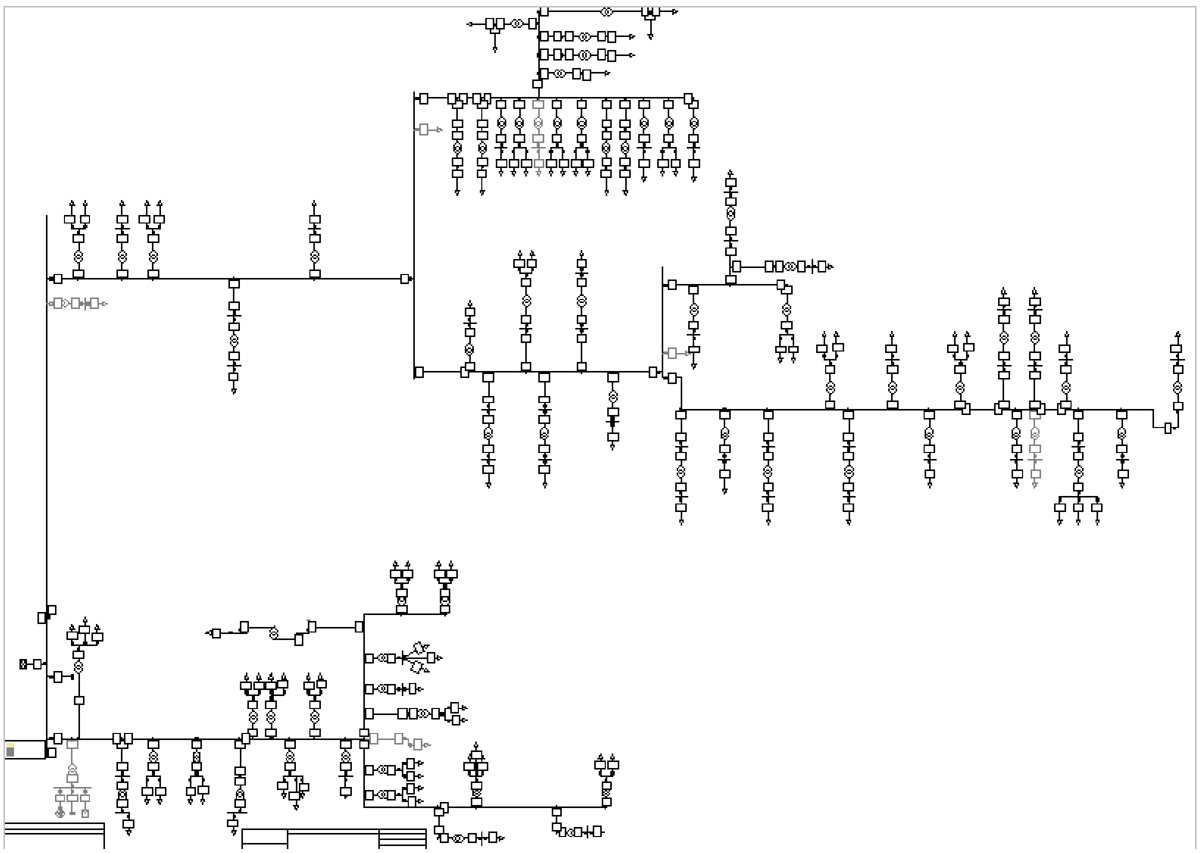


Figure 3.7. Complete PowerFactory model of the Estrela da Ilha distribution network

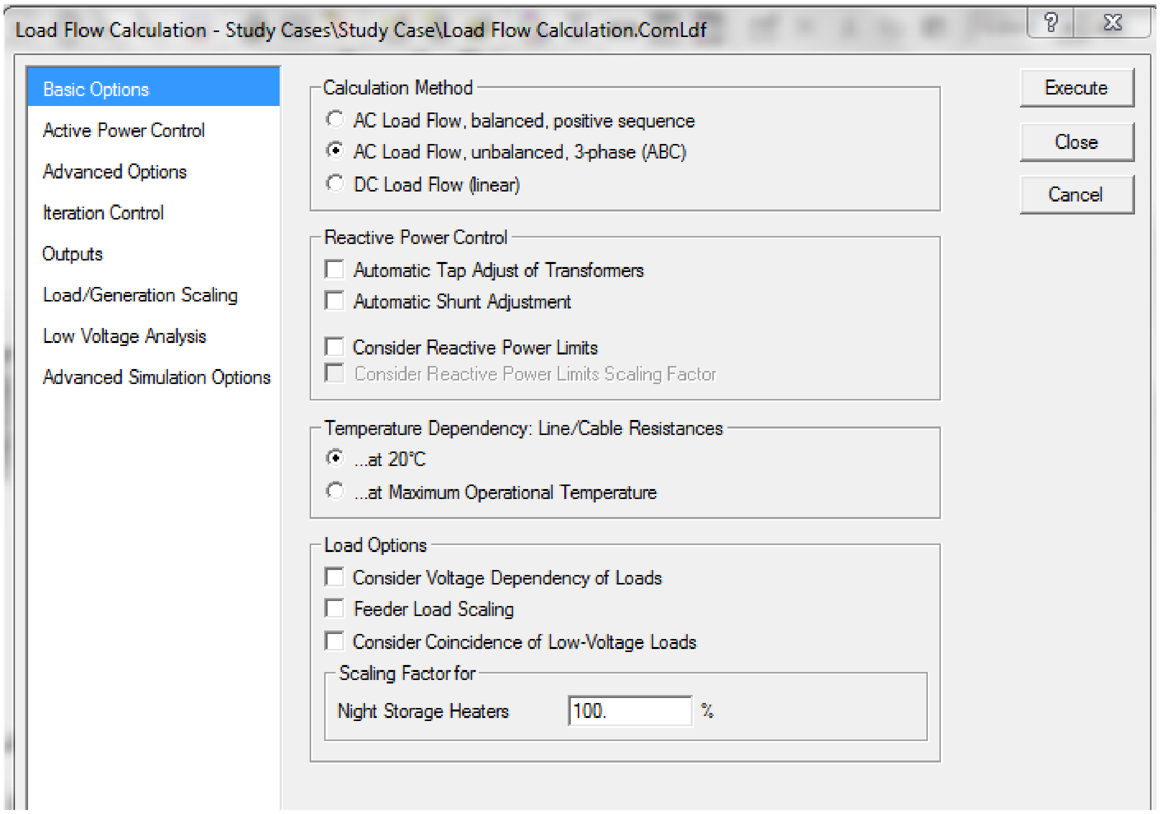


Figure 3.8. Power flow configuration dialog of PowerFactory

A code snippet written to configure and execute load flow in PowerFactory using Pyhon is given bellow.

```
app = powerfactory.GetApplication() # get application instance
LDF = app.GetFromStudyCase("comLdf") # get load flow instance
try:
   LDF.iopt_net = 1 # Calculation method 0-Balance AC | 1-Unbalance AC
   LDF.vlmin = 0.95 # set lower limit of allowed viltage
   LDF.vlmaxc = 1.05 # set upper limit of allowed viltage
   LDF.loadmax = 110 # set maximum allowed loading
   LDF.Execute() # excecute the poer flow command
except Exception:
```

```
logging.info("Exception runPF")
exc_type, exc_value, exc_traceback = sys.exc_info()
lines = traceback.format_exception(exc_type, exc_value, exc_traceback)
logging.info(''.join('!! ' + line for line in lines))
from traceback import print_exc
print_exc()
```

Appendix D.1 shows the result of the power flow analysis for the worst case scenario with all loads set to their maximum demand with a 0.8 power factor.

3.1.2.1.7. Reliability analysis

Reliability analysis investigated the total electrical interruptions for loads during the operational period. PowerFactory uses statistical methods to do the reliability analysis. Reliability analysis can also be done via graphical user interface or Python code. Figure 3.9 shows the reliability analysis configuration dialog of PowerFactory.

Reliability analysis can be use to calculate expected interruption frequencies, annual interruptions costs, and compare alternative network designs (DIgSILENT, 2014). Figure 3.9 shows the basic configuration window of the reliability analysis. PowerFactory also supports a number of advance configurations in the reliability analysis similar to the power flow analysis.

The code segment below shows how to configure important parameters of the reliability analysis via Python and how to execute the reliability analysis command in PowerFactory:

```
app = powerfactory.GetApplication() # get application instance
Rel = app.GetFromStudyCase("ComRel3") # get reliability analysis instant
```

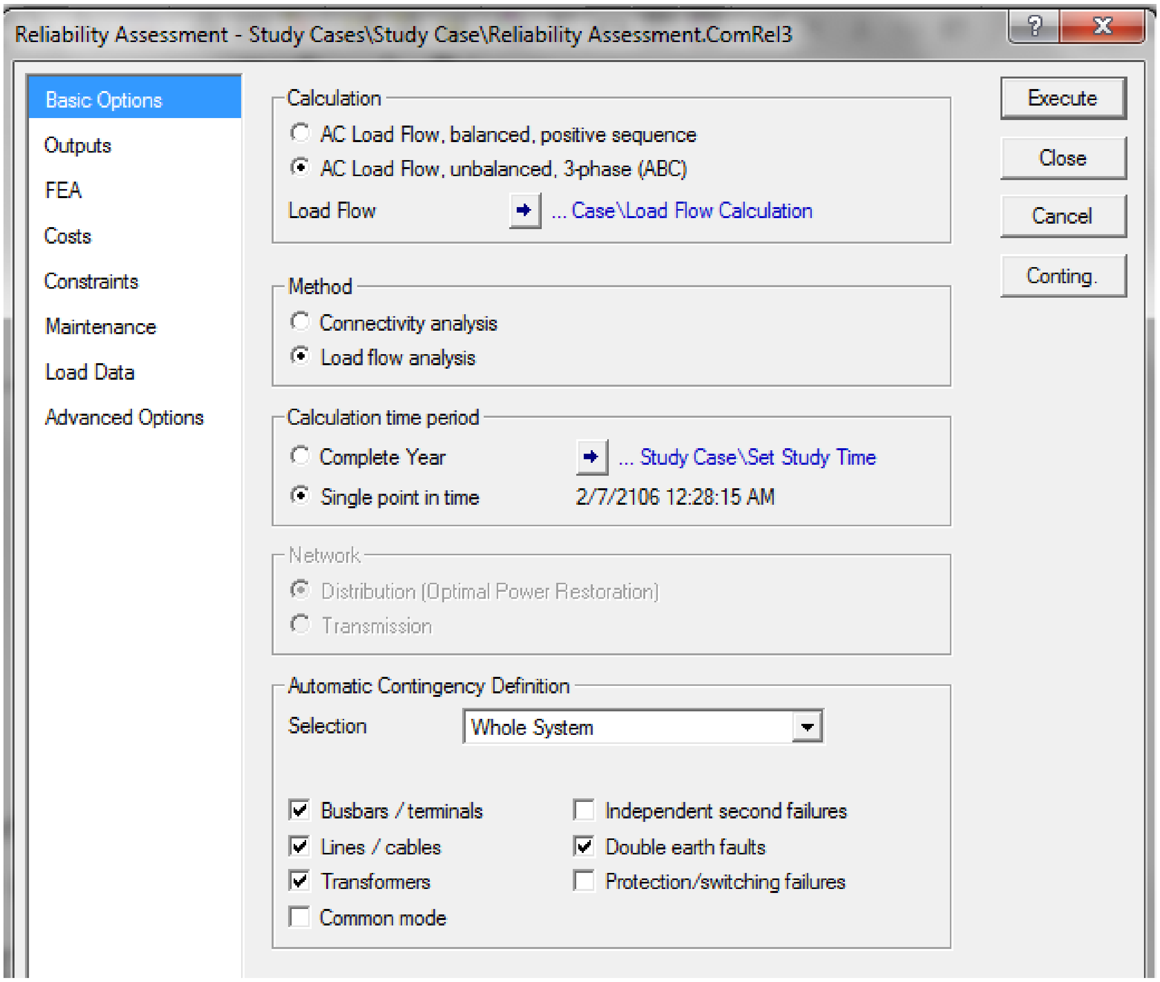


Figure 3.9. Reliability analysis configuration dialog of PowerFactory

```
try:
    Rel.vlmin_ldf = 0.95 # set min voltage set point for load flow
    Rel.vlmax_ldf = 1.05 # set max voltage set point for load flow
    Rel.loadmax = 110 # set maximum allowed loading
    Rel.Execute() # excecute the reliability abalysis command
except Exception:
    logging.info("Exception runPF")
    exc_type, exc_value, exc_traceback = sys.exc_info()
```

```
lines = traceback.format_exception(exc_type, exc_value, exc_traceback)
logging.info(''.join('!! ' + line for line in lines))
from traceback import print_exc
print_exc()
```

Appendix E.1 shows the sample results for the reliability analysis without DERs. The results include sample output for a transformer, line segment and a terminal.

3.1.3 External smart grid emulator

Smart grid emulator is an optional part of the DER allocation tool. A Smart grid emulator is a hardware system that can be interfaced to any PowerFactory model developed. The emulator was developed as a result of DOE (Department of Energy) grant. The system was used in laboratories to give students and understanding of the AMI and how to configure and collect data from smart meters. Emulator incorporates an Advanced Metering Infrastructure in the distribution network with hardware controlled loads. The emulator was connected to the PowerFactory and hence the agent based system via python. MAS updates the PowerFactory model and run power flow analysis in every tic with updated loads with the demand corresponds to that time tic. Each hardware load can be allocated to a selected software load in the PowerFactory. Python script running will collect results of the power flow and feed them to the loads in smart the grid emulator.

Hardware and software parts of the emulator are integrated via USB to I^2C converter with the support of Input-Output expander. Once the MAS is running, python collects the voltage and current data from the corresponding loads in the

PowerFactory and feeds them to the controller of the loads. The following section presents the detail description of the integration and load control.

3.1.3.1. Integrating power system simulator with smart grid emulator hardware

Integration of the hardware controllable loads with a power system simulator was done via Sub-20 USB to multi-protocol converter. Figure 3.10 shows the functional diagram of the overall emulator. Once the voltage and current data are calculated from the power system simulator, an intermediate program is used to extract this data and generate the signals that feed in to the external hardware. Intermediate program generates the USB command to Sub-20 depending on the load number (i) and the voltage of load i at time t ($V_i(t)$). Once this command is received by the Sub-20, it will convert the command to I^2C command and send it to the I/O expander in the Load Control Board i (LCB_i). I/O expander will turn on and off its outputs according to the I^2C command, which in turn controls the voltage of the hardware load i (L_i). Figure 3.11 and Figure 3.12 both show the load control board design.

3.1.3.2. Hardware controllable loads and metering network

Figure 3.13 shows the hardware portion of the Smart Grid emulator. The hardware potion consists of hardware loads, load control boards, smart meters, voltage indicators and the SUB-20 which facilitates the integration of the software portion. The control board consists of an I/O expander which communicates using I^2C protocol. The load control board uses reconfigurable potential divider technique to control the voltage across the load resistor. Voltage can be changed between 5% in ten discreet steps. Once the control signal is received from the intermediate

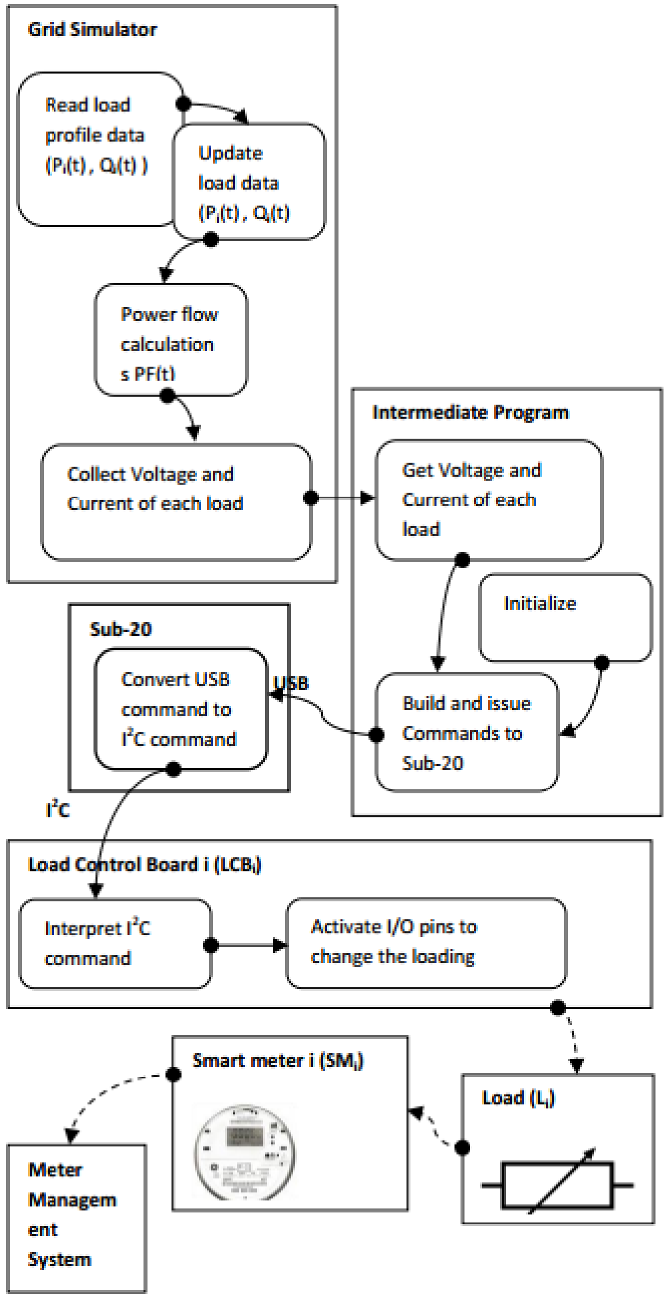


Figure 3.10. Smart gird emulator functionality block diagram

program, I/O expander will activate the corresponding output pins. This will short some of the resistors in the potential divider arrangement shown in 3.12. This change in configuration will change the voltage across the load resistor. A smart

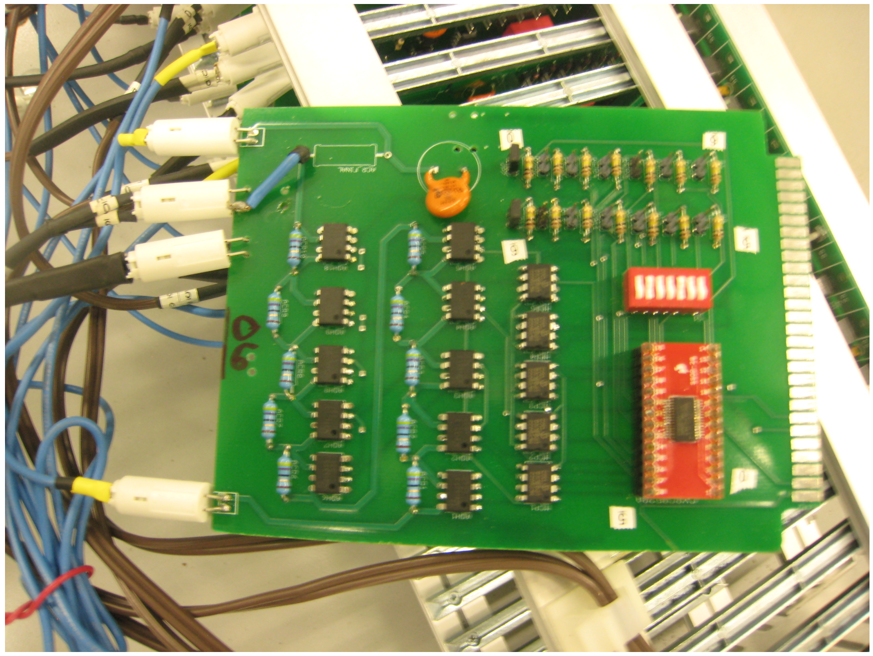


Figure 3.11. Load control board hardware design

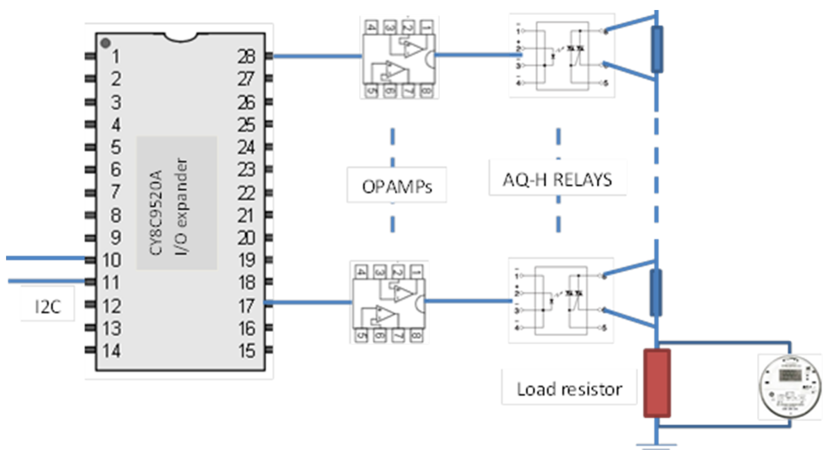


Figure 3.12. Load control board block diagram

meter is connected across the load resistor in each board and displays and records the voltage variation of the load. Smart meters communicate with the meter management system via the AMI network and record the voltage variation data.

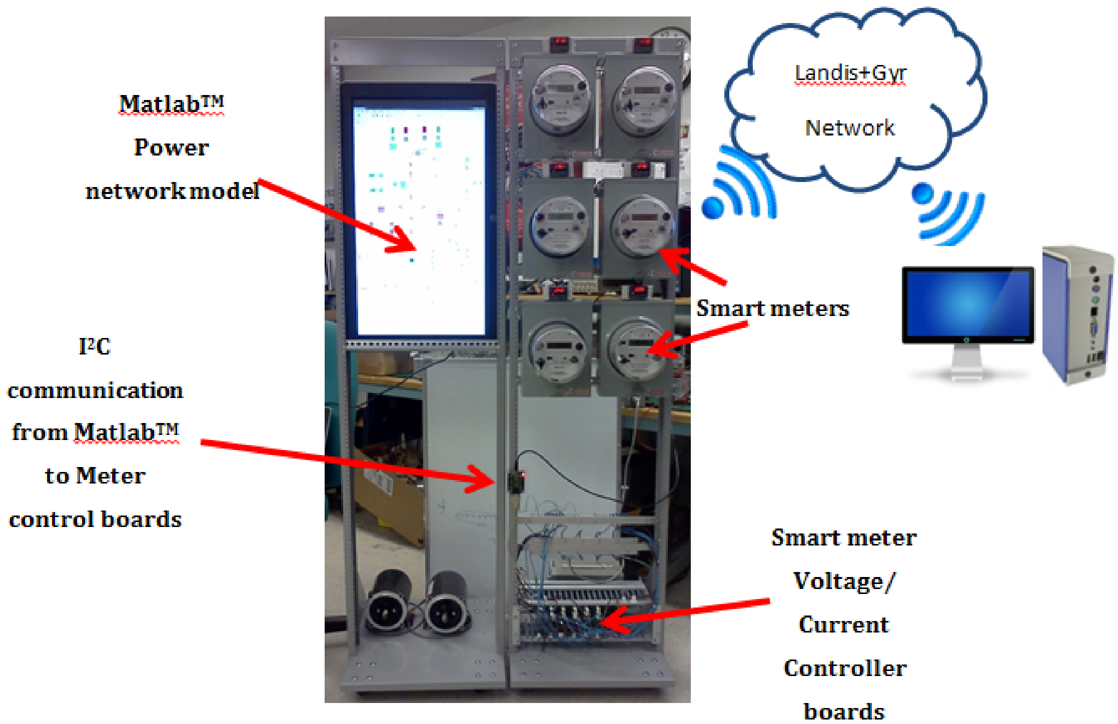


Figure 3.13. Hardware portion of the smart grid emulator

The data stored in the meter management system can later be analyzed to see the behavior of these loads throughout the planning process.

3.1.4 Framework for Agent based system

The Agent based system described in chapter 3.2 is based on a geographical model. This involves representing all the load points, transformers if necessary and any other components such as DER units in a GIS map and mapping them to the PowerFactory model. This section describes the frame work required for the GIS representation and mapping between the MAS and the PowerFactory.

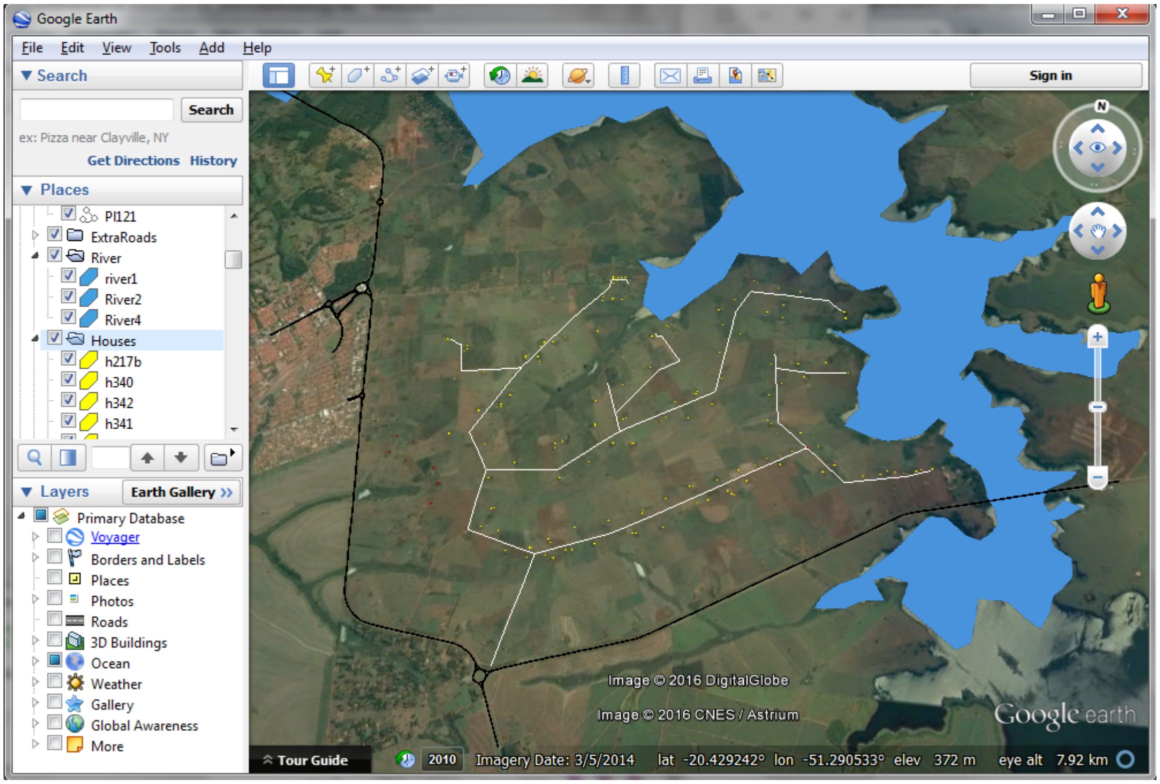
3.1.4.1. Construction of GIS map

The GIS map was constructed using Google Earth and MapWindows GIS (Map Windows OSS, 2013). Google Earth was used to identify the load points and power network layout. Figure 3.14 shows the Estera da Ilha power distribution network marked in Google Earth. Figure 3.14 consists of power distribution lines in white, main road network in black, load points in yellow and a nearby river in blue. All items are marked on the map using polygons and lines. These polygons and associated details (coordinates and other attributes) can be converted to shape-files. Shape-files are used in GIS systems to super impose important objects on a given map.

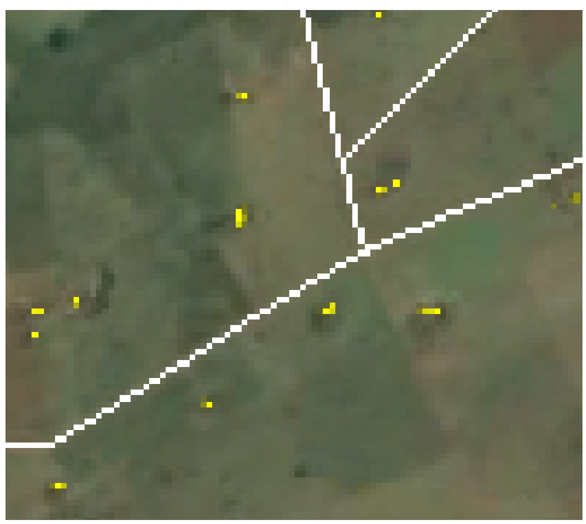
The line and polygon objects created in Google Earth can be saved in Keyhole Markup Language format as".kmz" files. Keyhole Markup Language is an XML notation for expressing geographic annotation and visualization within Internet-based, two-dimensional maps and three-dimensional Earth browsers.

In order to import these to Agent based system ".kmz" files should be converted to the shape file format ".shp". There are many web tools available for this purpose. MyGeoData - GIS Data Converter was used to convert ".kmz" data to ".shp" in this project (MyGeoData, 2014).

After generating shape-files, additional attributes to the shapes can be added using mapWindow GIS. Figure 3.15 shows the user interface of MapWindow GIS software. The attribute of each shape file can be altered using the attribute editing table shown in figure 3.16. These attributes can be used to represent the unique features of a shape and to represent the relationship with the PowerFactory network model. As an example column "loadName" in figure 3.16 matches the shape to the load point in the PowerFactory and column "trafo" represent the transformer name of which the load is connected to in powerFactory.



(a) Complete map of the network showing roads (in black) and electrical power lines (in white)



(b) Zoomed GIS map showing the load points

Figure 3.14. GIS map creation using Google Earth

Once built, the shape-files and configured attributes in the shape-files are ready to use in agent based system.

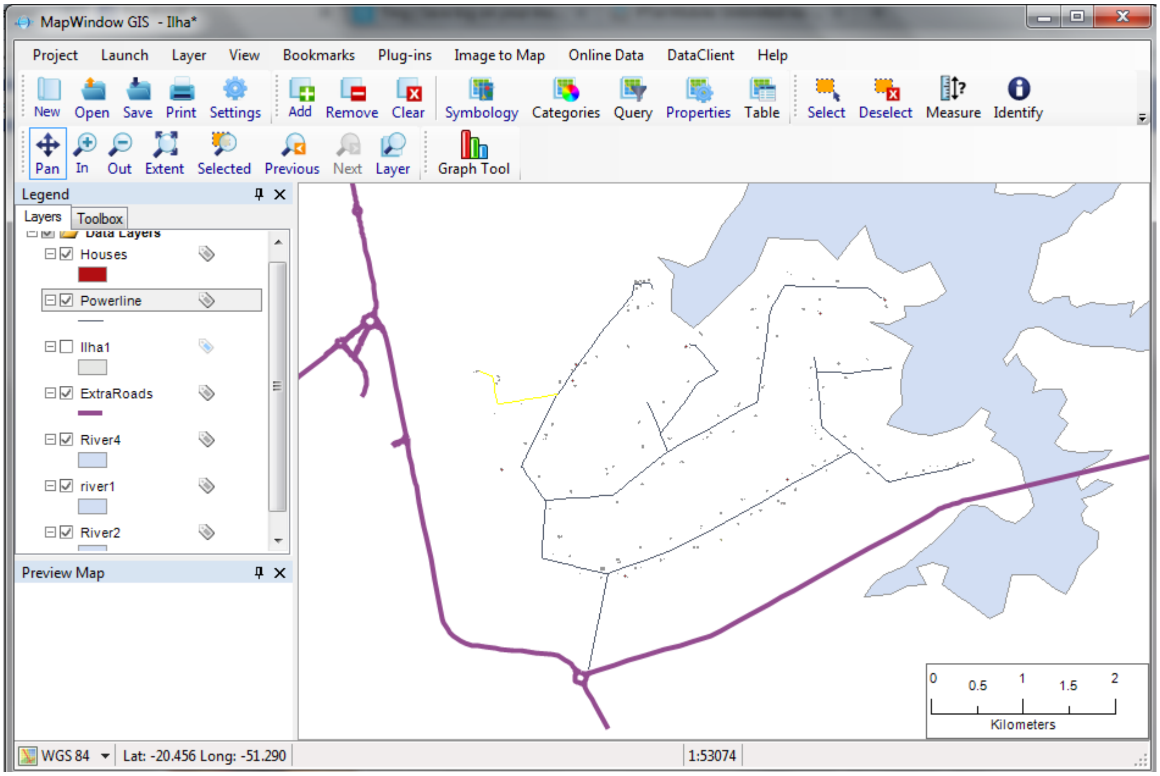
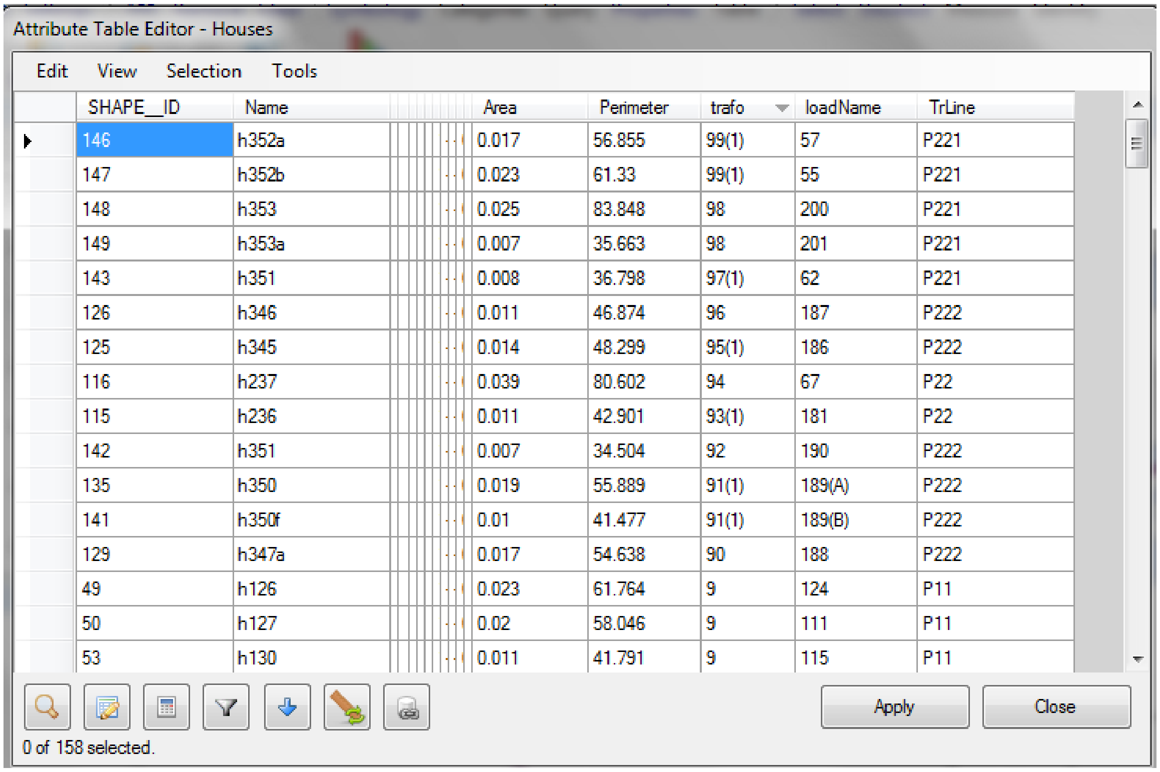


Figure 3.15. MapWindow GIS software to modify shape-files

3.2 Multi agent system

Multi Agent System was developed using a MAS development tool called "Repast Simphony". which is an open source tool. MAS can be developed in Repast Simphony using multiple languages. In this research java was used as the Programming language to develop MAS.

In Repast Simphony the modeled world can be represent either as a grid or as a GIS with real map. The grid base representation does not account the actual physical location characteristics of an agent. To represent the physical location and in order to get the GIS data, agents are needed to associate with a coordinate system. The value of this research is that it captures the agent's physical location and collects GIS data such as weather data, terrain data from real world data bases.



SHAPE__ID	Name	Area	Perimeter	trafo	loadName	TrLine
146	h352a	0.017	56.855	99(1)	57	P221
147	h352b	0.023	61.33	99(1)	55	P221
148	h353	0.025	83.848	98	200	P221
149	h353a	0.007	35.663	98	201	P221
143	h351	0.008	36.798	97(1)	62	P221
126	h346	0.011	46.874	96	187	P222
125	h345	0.014	48.299	95(1)	186	P222
116	h237	0.039	80.602	94	67	P22
115	h236	0.011	42.901	93(1)	181	P22
142	h351	0.007	34.504	92	190	P222
135	h350	0.019	55.889	91(1)	189(A)	P222
141	h350f	0.01	41.477	91(1)	189(B)	P222
129	h347a	0.017	54.638	90	188	P222
49	h126	0.023	61.764	9	124	P11
50	h127	0.02	58.046	9	111	P11
53	h130	0.011	41.791	9	115	P11

Figure 3.16. Attribute edit table of MapWindow GIS software

Section below describes the individual agents and their characteristics in the developed multi agent system.

3.2.1 Agent model

A brief introduction of the agents in the MAS is provided below and will discuss in details in following sections.

- **Coordinator agent**

  Global agent who maintain the time count. Coordinator agent also communicate with PowerFactory through Python program to perform power flow analysis and reliability analysis to collect relevant data for the other agents.

- **building / Load agents**

  Represent each load point in the selected network. Each load agent represent the behavior of the customer/customers in the house/building. The demand profile of each building/ household is determined based on this behavior.

- **Weather agents**

  Weather agents are distributed among the area of interest here after denoted as world. Weather agents collect past weather data corresponds to its geographical location and will update its data as time advance.

- **Demand agents**

  Demand agent represents a collection of load agents. Demand agents can be distributed in the world in the same way as the weather agents or can be assigned as one for a transformer.

- **DER agents**

  After the initial placement , DER agent travel across the world to find the best location for a DER placement. In its journey DER agent interact with load agents, demand agents, weather agents and grant agent to find the best capacity, location and the type of energy resources to be used.

- **Grant agents**

  Grant agent receives bids from demand agents for each location and the capacity. After analyzing the bids grant agent rewards the DER agent for its bid. The value of reward determine weather the bid is granted or not and how feasible is the bid. The DER agent analyze these rewards to learn the DER placement capability and the best location, capacity pair.

Figure 3.17 shows the higher level interactions among agents and figure 3.18 shows the overview of the MAS functionality. The sections below will discuss the behavior of each agent in details.

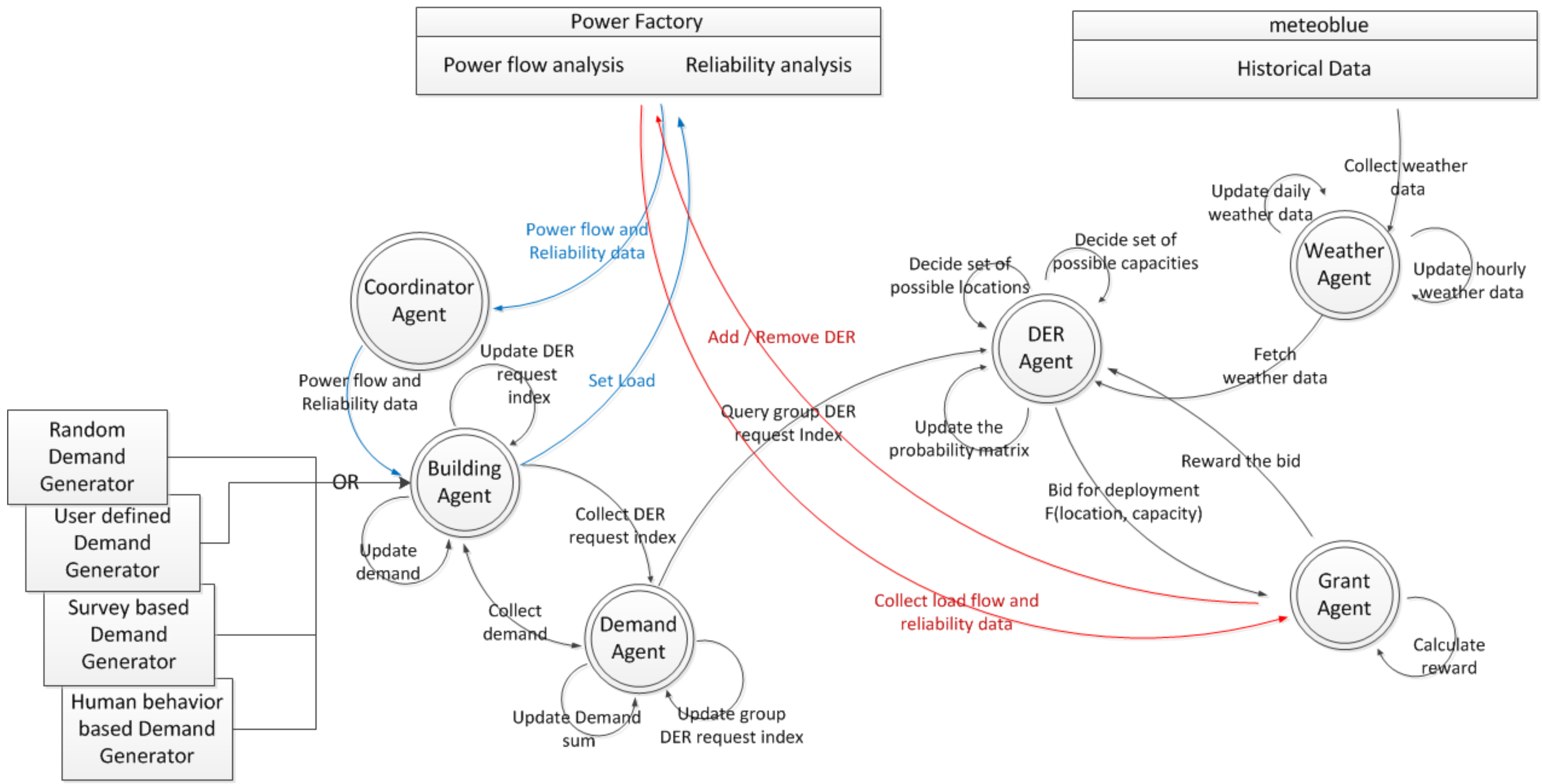


Figure 3.17. Agent interaction modeled in Repast Simphony

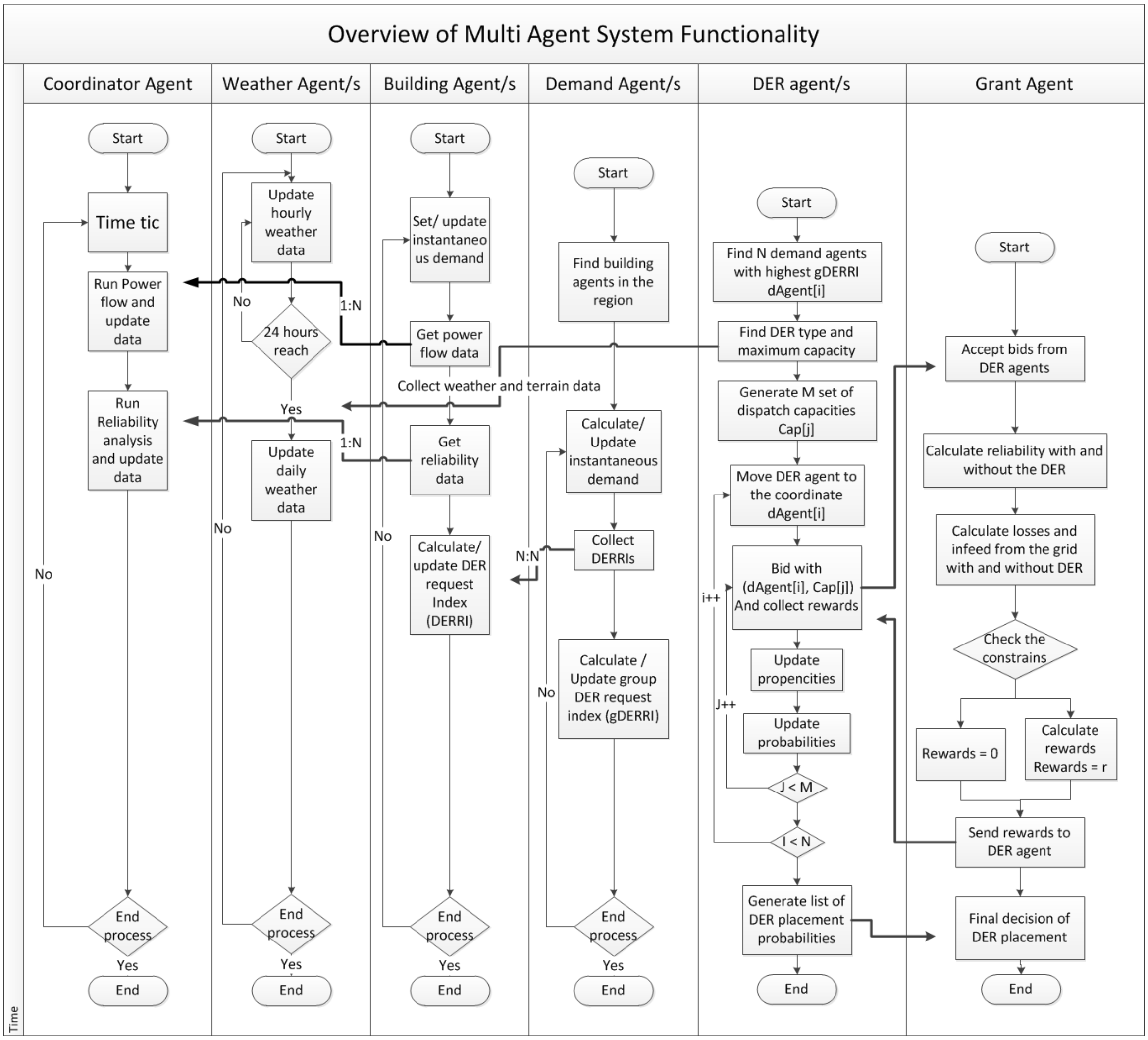


Figure 3.18. Overview of Multi Agent System functionality

3.2.1.1. Coordinator agent

The coordinator agent is unique to the world. The first responsibility of the coordinator agent is to coordinate the time in the world. Coordinator agents maintain the relative time from the start of the simulation. In each step of the simulation, time advance in a unit. One unit in the simulation is corresponds to one hour in the real world. Coordinator agent also interacts with PowerFactory to execute load flow and reliability analysis in the PowerFactory model. The results of load flow and reliability analysis are made globally available for all the agents in the system.

3.2.1.2. Building agent

Building agents access the reliability and power flow data provided by the coordinator agent to update their DER request index (DERRI). This is the index which determines how urge the building agent to have a distributed generation close to it. DERRI for the building agent i is a function of its demand (D_i), active and reactive power losses seen by the connected transformer ($P_{TrLoss,j}$ and $Q_{TrLoss,j}$), Load Point Interruption Frequency ($LPIF_i$) and Load Point Interruption Time ($LPIT_i$).Equation 3.1 shows how the DERRI was calculated using the above mentioned parameters.

$$DERRI = \frac{D_i}{\sum_i^{N_i} D_i} + \frac{P_{TrLoss,j}}{\sum_j^{N_j} P_{TrLoss,j}} + \frac{Q_{TrLoss,j}}{\sum_j^{N_j} Q_{TrLoss,j}} + \frac{LPIF_i}{\sum_i^{N_i} LPIF_i} + \frac{LPIT_i}{\sum_i^{N_i} LPIT_i} \tag{3.1}$$

Where N_i is the number of loads in the network and the N_j is the number of transformers in the network.

Building agents are responsible of collecting demand data and update demands in PowerFactory model at each time step to create a time varying demands in the PowerFactory loads. Demand agents can create its instantaneous demand using four methods, randomly created demands, user defined demands, demand queried from a spreadsheet tool created by survey data or using consumer behavior model.

- **Randomly created demand**

Random demands are created in a way that, demands are normally distributed between its base load and the maximum demand specified in the user interface.

- **User defined demand**

  User can specify hourly demand for 24 hours in the user interface to create user defined demand.

- **Demand created by a survey**

  A spread sheet tool can be used to generate demands from a survey data. Survey can be conducted for a selected sample of the population within the area of interest. Spread sheet tool can be access via the user interface and updated based on data collected from a survey. When program runs it will automatically collect the data from the spreadsheet depending on the time information generated by the coordinator agent. The spread sheet tool generates hourly data for weekdays, weekends, and for different seasons providing more detailed load profile data. .

- **Demand created using customer behavior**

  The user behavior was defined based on the different appliances used by the user and the time of their use. The detailed description of the customer behavioral model is given in appendix C. The advantage of this approach is that usage data is generated within the program and internal signal can be send to each customer to change their behavior to study the impact of the behavior changes in the grid (not implemented in this research).

Figure 3.19 shows the initial configuration window of the DER allocation tool.

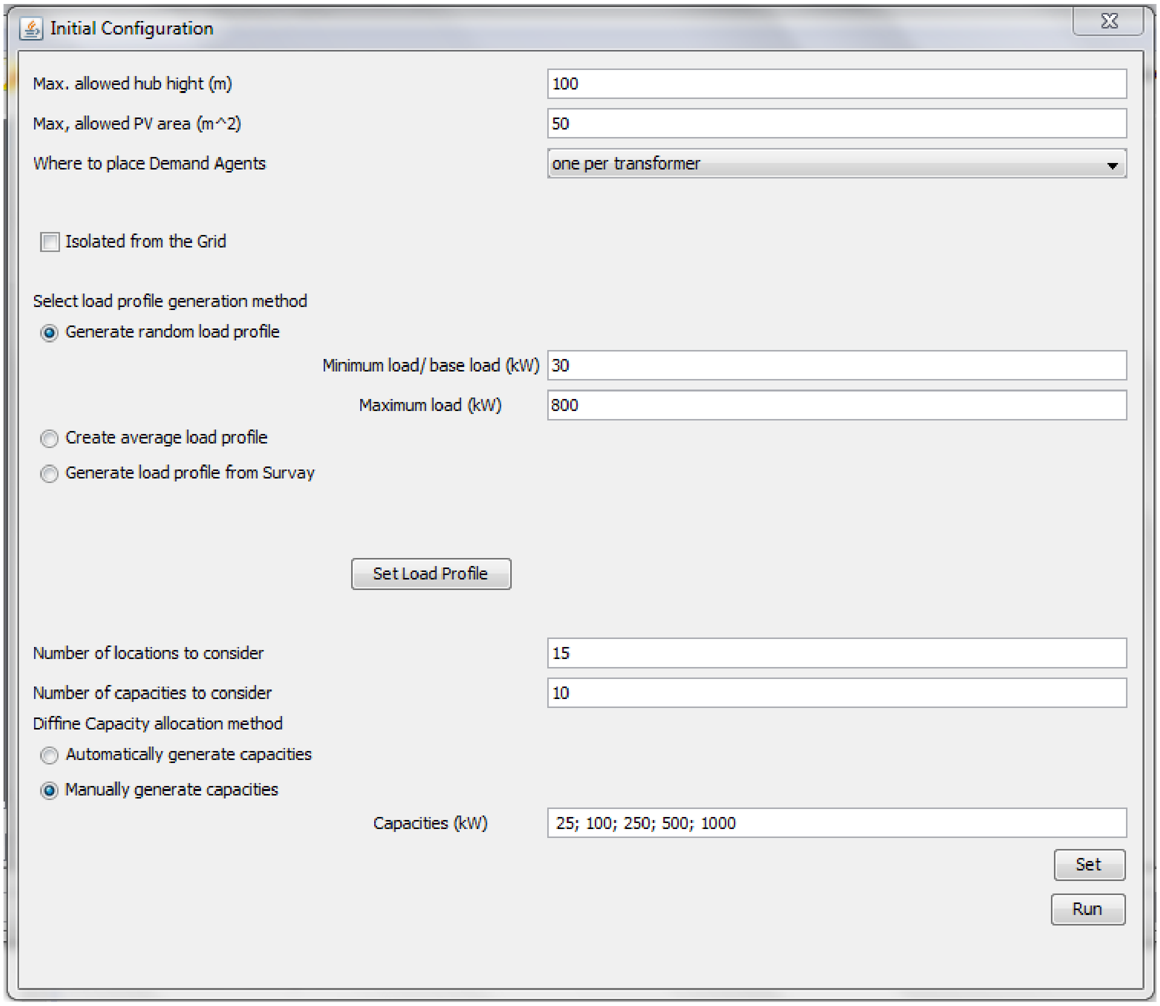


Figure 3.19. Graphical user interface for initial configuration of the DER allocation

3.2.1.3. Demand agent

Demands agent represent a collection of building agents and fetch their DERRIs to create group DERRI (gDERRI) using equation 3.2.

$$gDERRI_i = \frac{\sum_k^{N_b} DERRI_k}{N_b} \tag{3.2}$$

Where N_b is the number of building agents associated with the demand agent i

Demand agents can be created in the world in two ways. Demand agents can be associated one for a segment or can be associated as one for each transformer. Demand agents calculate their aggregated demand based on the instantaneous demands of its child building agents. gDERRI and the aggregated demand of each Demand agents are available to the DER agents.

3.2.1.4. Weather agents

Weather agents are distributed in the world as one agent per segment. World is divided into number of equally sized segments depending on the size of the world. Weather agents are located at the center of the each segment. Each weather agent can fetch weather information based on its location from a data collected in real world weather stations. These information consists of daily and hourly historical data needed by the DER agents to decide their DER type and the maximum possible capacity. In the current build the tool is only consider solar PV and wind as the possible DER generation types. Weather data such as solar radiation, cloud percentage, wind speed and wind direction are collected to facilitate the decisions of DER agents. Terrain data are also collected from the weather agent to investigate the terrain for solar PV placement. Weather agents can fetch their data in two ways. The historical data can be fetch from the spread sheet files prior downloaded from the *meteoblue* (n.d.). Meteoblue provide set of APIs to access their on-line data base to fetch current and predicted weather data.

Figure 3.20 shows the sample spreadsheet format of prior downloaded weather data. The information contains latitudes and the longitudes of the selected locations, description of the data entry types and corresponding units and the data entries. The 5 years of historical data was used for this project starting from

January 2010. Both hourly and monthly data were available for the use in the project.

```
LAT;−20.43;−20.43;−20.43;−20.43;−20.43;−20.43;−20.43
LON;−51.3;−51.3;−51.3;−51.3;−51.3;−51.3;−51.3
ASL;362;362;362;362;362;362;362
CITY;20.43 S −51.3 W ;20.43 S −51.3 W ;20.43 S −51.3 W ;20.43 S −51.3 W ;20.43 S −51.3 W ;20.43 S −51.3 W ;20.43 S −51.3 W
DOMAIN;SA01;SA01;SA01;SA01;SA01;SA01;SA01
SLAT;−20.513;−20.513;−20.513;−20.513;−20.513;−20.513;−20.513
SLON;−51.2161;−51.2161;−51.2161;−51.2161;−51.2161;−51.2161;−51.2161
XPOS;133;133;133;133;133;133;133
YPOS;239;239;239;239;239;239;239
SELV;342;342;342;342;342;342;342
CODE;11;31;32;52;61;74;204
LEVEL;2mabovegnd;10mabovegnd;10mabovegnd;2mabovegnd;sfc;midcldlay;sfc
NAME;Temperature;Winddirection;Windspeed;Relativehumidity;TotalPrecipitation;Mediumcloudcover;ShortwaveRadiation−backwards
UNIT; C ;    ;m/s;%;mm;%;W/m2
AGGREGATION_CODE;0;0;0;0;0;0;0
AGGREGATION;;;;;;;
UTC_OFFSET;0;0;0;0;0;0;0
LOCATION_ID;0;0;0;0;0;0;0
2010−01−01T00:00;25.26;274.76;1.2;92.37;0;100;0
2010−01−01T01:00;25.18;282.53;0.92;92.47;0;100;0
2010−01−01T02:00;25.15;277.13;0.81;92.03;0;100;0
2010−01−01T03:00;25.15;270;0.6;91.15;0;100;0
2010−01−01T04:00;24.83;243.43;0.67;92.62;0;100;0
2010−01−01T05:00;24.43;209.05;1.03;94.64;0;100;0
2010−01−01T06:00;24.2;184.4;1.3;96.19;0;100;0
2010−01−01T07:00;24.05;171.87;1.41;97.35;0;100;0
2010−01−01T08:00;24.07;150.64;1.84;97.23;0;100;0
2010−01−01T09:00;24.01;133.36;2.48;96.94;0;100;1
2010−01−01T10:00;24.88;116.57;3.8;92.96;0;100;97
2010−01−01T11:00;25.68;107.7;4.93;87.84;0;100;251
```

Figure 3.20. Sample spread sheet format of prior downloaded weather data

3.2.1.5. DER agents

DER agents collaborate with weather agents, demand agents and the grant agent to take the decision of its location, type and the capacity. DER agent collects gDERRI from all the demand agents and calculates the set of possible locations to place DERs. The DER type and the maximum capacity are calculated for each of these locations based on a historical analysis of weather data. One year worth of weather data and terrain data were analyzed to decide the DER type and maximum possible capacity for each location. Set of capacities are generated randomly based on the maximum capacity calculated. The set contains normally distributed random set of capacities from 10 kW to the maximum possible capacity. Once the location and the capacity set are formed DER agent start bidding processes. DER agent travel among the pre calculated locations in each simulation time step. At each location DER agent bids for the place with the different capacities in the capacity set. Each bid happens in the different time step with different loading in the network. This behavior helps to covers multiple scenarios for different times of the day and for different seasons. DER agent receives rewards from the Grant agent for each of its bids. The reinforced learning was used by the DER agent to learn the feasibilities of each location and capacity pair based on the rewards received in the bidding process.

3.2.1.6. Grant agent

Grant agent receives the bids generated from the DER agent and analyses for the objectives and the constraints. Multiple objective functions are considered in the optimization process namely,

- minimizing the System Average Interruption Frequency Index (SAIFI)

- minimizing the System Average Interruption Duration Index (SAIDI)
- minimizing the total losses in the network
- minimizing the percentage demand unmet
- maximizing the DER loading while satisfying the constrains

SAIFI in per average customer and SAIDI in hours per average customer are shown in equation 3.3 and 3.4

$$SAIFI = \frac{\sum_i^{N_i} ACIF_i \times C_i}{\sum_i^{N_i} Ci_i} + \tag{3.3}$$

$$SAIDI = \frac{\sum_i^{N_i} ACITI_i \times C_i}{\sum_i^{N_i} Ci_i} + \tag{3.4}$$

Where,

$ACIF_i$ is the average Customer Interruption Frequency for customer i

$ACIT_i$ is the average Customer Interruption Time for customer i

C_i is the number of customers supplied by load point i

N_i is the number of load points

The constraints to be satisfied are that the increase of the system losses has to be less than 5% of the total loads in the network and the loading of the DER has to be less than the 95% of its nominal power.

Grant agents reward the DER agent depending on how good these objectives and constraints are satisfied. DER agent updates its propensity matrix and the probability matrix based on the rewards granted by the grant agent. The propensity and probability matrices were created so that each location is represented by the columns and each capacity is represented by the rows. The bidding process can be iterative to cover longer time periods and include as many scenarios as needed. At each bid the probability updates from the propensity matrix. The probability matrix has the same structure as the propensity matrix, with columns representing the locations and rows representing the capacities. At the end of the bidding process, DER agent will have completed probability matrix which is used to take the final decision of DER placements.

3.2.2 Decision making process

After bidding for all the locations with all the capacities final propensity and probability matrices for that cycle will get updated by the learning process. If desired simulation can be run for number of cycles before making the final decision. An increased number of cycles can help the simulation perform for longer period of time in the real world lasting for months or even years. Expanded simulation times will help cover most of the possible scenarios including seasonal changes and other special situations. Once all the cycles are covered as required, the final update of the probability matrix can be used for the decision making. Each element of the probability matrix is scanned to identify the element that satisfies the conditions specified in the next section. This element is corresponds to the best location for a DER placement and its capacity. If a number of probabilities are detected close to the selected probability, these locations can be considered as alternative positions if more than one DER is required. Since this tool doesn't perform economic analysis, the results obtained from this can be used in available economic analysis tool to find the economical feasibility of the solution. Multiple locations selected with high probabilities can be used in economic analysis with the chosen capacities to get an optimal solution for DER placement.

3.2.3 Multi function optimization

The decision making process will eventually solve a multi function optimization problem. As discuss previously grant agent rewards were generated to satisfy the objectives of

- minimizing the System Average Interruption Frequency Index (SAIFI)
- minimizing the System Average Interruption Duration Index (SAIDI)
- minimizing the total losses in the network
- minimizing the percentage demand unmet
- minimizing the DER loading

while satisfying the constrains:

- increase of the system losses if any has to be less than 5% of the total loads
- loading of the DER has to be less than the 95% of its nominal power

To solve this problem **weighted sum approach for the multifunction optimization** was used with the above mentioned constrains. The optimization was not performed using traditional optimization techniques but using reinforced learning approach. During the reinforced learning, DER agent bids with a location and a capacity value. Grant agents who receives the bids at each time step perform a reliability and load flow analysis on the network with the DER and the current demand values corresponding to that time step. The results of the reliability analysis and the load flow determine the reward value granted to the DER agent for a given bid. The reward value at a given time step t is calculated using the equation 3.5.

$$R(t) = \alpha \times \text{SAIFIdiff} + \beta \times \text{SAIDIdiff} + \gamma \times \text{GridLossDiff}$$
$$+ \delta \times \text{DERloading} + \mu \times \text{PercentageDemandUnmet} \quad (3.5)$$

where

$$\text{SAIFIdiff} = \frac{\text{SAIFI}_{\text{with DER}} - \text{SAIFI}_{\text{without DER}}}{\text{SAIFI}_{\text{without DER}}}$$

$$\text{SAIDIdiff} = \frac{\text{SAIDI}_{\text{with DER}} - \text{SAIDI}_{\text{without DER}}}{\text{SAIDI}_{\text{without DER}}}$$

$$\text{GridLossDiff} = \frac{\text{GridLoss}_{\text{with DER}} - \text{GridLoss}_{\text{without DER}}}{\text{GridLoss}_{\text{without DER}}}$$

$$\text{DERloading} = \frac{\text{Output power of DER}}{\text{Rated capacity of DER}}$$

$$\text{PercentageDemandUnmet} = \frac{\text{TotalDemand}_{\text{with DER}} - \text{DER capacity}}{\text{TotalDemand}_{\text{with DER}}}$$

the weight values α, β, γ, δ, and μ are determined based on the relative importance of each objective. In the current version these values can be specified by the user at initial state.

The propensity matrix and the probability matrix are updated based on the reward values. Probability matrix determine the reward for a given location and a capacity, relative to the rewards for other locations and the capacities. The selection of the best location and the capacity was performed based on the entries in probability matrix. Two different selection criteria were defined.

- **Maximize the reward:**

  When maximizing the rewards DER capacity optimization was ignored. The only focus is to find the optimal location. This criteria intern get the maximum DER capacity defined by the user or generated by the system.

  In this approach final probability matrix is scanned to find the element with the highest probability. If the element P_{ij} is found to be the highest probability, the j^{th} element in the considered location array gives the best location for the DER and the i^{th} location of the capacity array gives the selected capacity.

- **Minimize the DER capacity:**

  When minimizing the DER capacity, the best location to place the DER is found with the minimum capacity needed to fully satisfy the demand. The optimal probability P_{ij} is selected from the final probability matrix to satisfy the following criteria.

$$P_{ij} > P_{\text{Threshold}} \tag{3.6a}$$

$$P_{ij} < P_{mn} \; \forall (m \neq i, n \neq j) \tag{3.6b}$$

where $m = 1, 2, 3..., N_{cap}$ and $n = 1, 2, 3..., N_{loc}$

and $P_{\text{Threshold}} = 0.005$, is used to eliminate the unfeasible solutions.

Then the corresponding location and the capacity is given by the j^{th} element of the location array and the i^{th} element of the capacity array.

3.3 Summary

This chapter provided the framework and methodology used to create the DER allocation tool. Chapter described the modeling of the network of interest, build the GIS components necessary for the graphical representation of the network in the MAS and the interaction of the agents in the MAS to achieve the goals of the DER allocation tool.The interactions of the agents in the MAS helped to find the best location/s, type/s and the capacity/s for a DER placement. The next chapter provides the results and the analysis.

CHAPTER 4. RESULTS AND CONCLUSIONS

This chapter discusses and analyses the results obtained from the DER allocation tool described in the previous chapter on the Estrela da Ilha network.

4.1 Prior to the introduction of DERs

The system under consideration was analyzed prior to the introduction of DERs to the system under consideration. The power flow analysis and the reliability analysis was performed for the worst case scenario to study the system behavior.

4.1.1 Power flow analysis

Power flow analysis was performed to verify the functionality of the system. The results obtained from power flow analysis is listed in appendix D. The worst case scenario was analyzed using power flow analysis to investigate the maximum demand from the grid and maximum possible loadings of the power system components. Result shown in appendix D list the active power flow, reactive power flow, power factor, current and loading of each element in the network.

It has been noted that no line segment in the network is overloaded and maximum loading seen in a line segment is 29.29%. A couple of transformers in the network has loading closer to 100%(109%, 103%, 93% and 88%). Loading of a transformer close to 100% is acceptable and in fact a frequently done by the utility to reduce losses in the transformer. Although this may be true, loading a transformer more than 100% for a long period of time is not recommended for the lifetime of a transformer. The total in-feed from the external grid to the network under consideration is 704.72 kW with 26.78 kW of grid losses.

4.1.2 Reliability analysis

Reliability analysis of the system was performed under worst case scenario to study the reliability of the system prior to the introduction of the distributed energy resources. It was noted that the system average interruption frequency index (SAIFI) was 0.7308 1/Ca and the system average interruption duration index (SAIDI) was 8.995 h/Ca. This tells us this system experience 0.73 interruptions per customer and an interruption last for 8 hours in average. There are other indexes that were calculated during the analysis and shown in E, but the main indexes of interest for the analysis of this theses are the SAIFI and the SAIDI.

4.2 introduction of DERs to the system using agent based simulation

The multi agent system was used to find the best locations and the capacities for the DERs in the network as described in methodology chapter. A propensity matrix was calculated and a probability matrix was derived for the system. Columns of both the propensity and the probability matrix represent the locations under consideration while the corresponding columns represent the capacities. Equation 4.1 and 4.2 shows the initial propensity matrix and the initial probability matrix populated by the system. In each iteration after the preprocessing the propensity matrix is updated and with that data probability matrix is updated. Equation 4.3 shows the partially propagated propensity matrix and equation 4.4 shows the corresponding probability matrix. Each column of the matrix is

Table 4.1
Geographical coordinates considered by DER agents for the placement of DERs after the preprocessing

Geographical coordinate considered by DER agents (latitude, longitude, 0.0)
(-51.28330493122459, -20.41209125812885, 0.0)
(-51.28925484836532, -20.42030088708961, 0.0)
(-51.30141341521276, -20.42685903000516, 0.0)
(-51.3000528105992, -20.41306568507541, 0.0)
(-51.26836980242612, -20.43123110983011, 0.0)
(-51.31595079247784, -20.42258244202963, 0.0)
(-51.28255368433408, -20.42861495473677, 0.0)
(-51.3119363457016, -20.43253886948136, 0.0)
(-51.29084991541184, -20.43492651154567, 0.0)
(-51.29931105706441, -20.44123651358428, 0.0)

Table 4.2
Capacities considered by DER agents for the DERs after the preprocessing

Capacities considered by DER agents (kW)
25.0
100.0
250.0
500.0
1000.0

corresponding to the locations shown in figure 4.1. The list of coordinates and capacities corresponding to these results are shown in table 4.1 and table 4.2

$$\begin{matrix} 0.001 & 0.001 & 0.001 & 0.001 & 0.001 & 0.001 & 0.001 & 0.001 & 0.001 & 0.001 \\ 0.001 & 0.001 & 0.001 & 0.001 & 0.001 & 0.001 & 0.001 & 0.001 & 0.001 & 0.001 \\ 0.001 & 0.001 & 0.001 & 0.001 & 0.001 & 0.001 & 0.001 & 0.001 & 0.001 & 0.001 \\ 0.001 & 0.001 & 0.001 & 0.001 & 0.001 & 0.001 & 0.001 & 0.001 & 0.001 & 0.001 \\ 0.001 & 0.001 & 0.001 & 0.001 & 0.001 & 0.001 & 0.001 & 0.001 & 0.001 & 0.001 \end{matrix} \tag{4.1}$$

$$\begin{matrix} 0.02 & 0.02 & 0.02 & 0.02 & 0.02 & 0.02 & 0.02 & 0.02 & 0.02 & 0.02 \\ 0.02 & 0.02 & 0.02 & 0.02 & 0.02 & 0.02 & 0.02 & 0.02 & 0.02 & 0.02 \\ 0.02 & 0.02 & 0.02 & 0.02 & 0.02 & 0.02 & 0.02 & 0.02 & 0.02 & 0.02 \\ 0.02 & 0.02 & 0.02 & 0.02 & 0.02 & 0.02 & 0.02 & 0.02 & 0.02 & 0.02 \\ 0.02 & 0.02 & 0.02 & 0.02 & 0.02 & 0.02 & 0.02 & 0.02 & 0.02 & 0.02 \end{matrix} \tag{4.2}$$

$$\begin{matrix} 0.001 & 0.001 & 0.001 & 0.001 & 0.001 & 0.001 & 0.001 & 0.001 & 0.001 & 0.001 \\ 0.001 & 0.001 & 0.001 & 0.001 & 0.001 & 0.001 & 0.001 & 0.001 & 0.001 & 0.001 \\ 2.5872 & 1.9153 & 1.9869 & 0.001 & 2.2523 & 1.8626 & 0.001 & 0.001 & 0.001 & 0.001 \\ 3.2283 & 2.5377 & 2.6297 & 2.6542 & 2.8704 & 2.5365 & 0.001 & 0.001 & 0.001 & 0.001 \\ 6.0773 & 5.4486 & 5.5257 & 5.6019 & 5.7898 & 0.001 & 0.001 & 0.001 & 0.001 & 0.001 \end{matrix} \tag{4.3}$$

$$\begin{matrix} 0.0001 & 0.0001 & 0.0001 & 0.0001 & 0.0001 & 0.0001 & 0.0001 & 0.0001 & 0.0001 & 0.0001 \\ 0.0001 & 0.0001 & 0.0001 & 0.0001 & 0.0001 & 0.0001 & 0.0001 & 0.0001 & 0.0001 & 0.0001 \\ 0.0466 & 0.0345 & 0.0358 & 0.0001 & 0.0406 & 0.0336 & 0.0001 & 0.0001 & 0.0001 & 0.0001 \\ 0.0582 & 0.0457 & 0.0474 & 0.0478 & 0.0517 & 0.0457 & 0.0001 & 0.0001 & 0.0001 & 0.0001 \\ 0.1095 & 0.0982 & 0.0995 & 0.1009 & 0.1043 & 0.0001 & 0.0001 & 0.0001 & 0.0001 & 0.0001 \end{matrix} \tag{4.4}$$

The red colored circles shown in figure 4.1 are the locations considered by the DER agents for DER placements. The DER agent will travel to each location during the simulation time and analyze for each of the capacities shown in table 4.2 at that location. The circle shown in cyan indicates the current position of the DER agent. After moving to all the locations and trying all the capacities DER agent will have complete propensity and probability matrices. We call this a complete cycle.

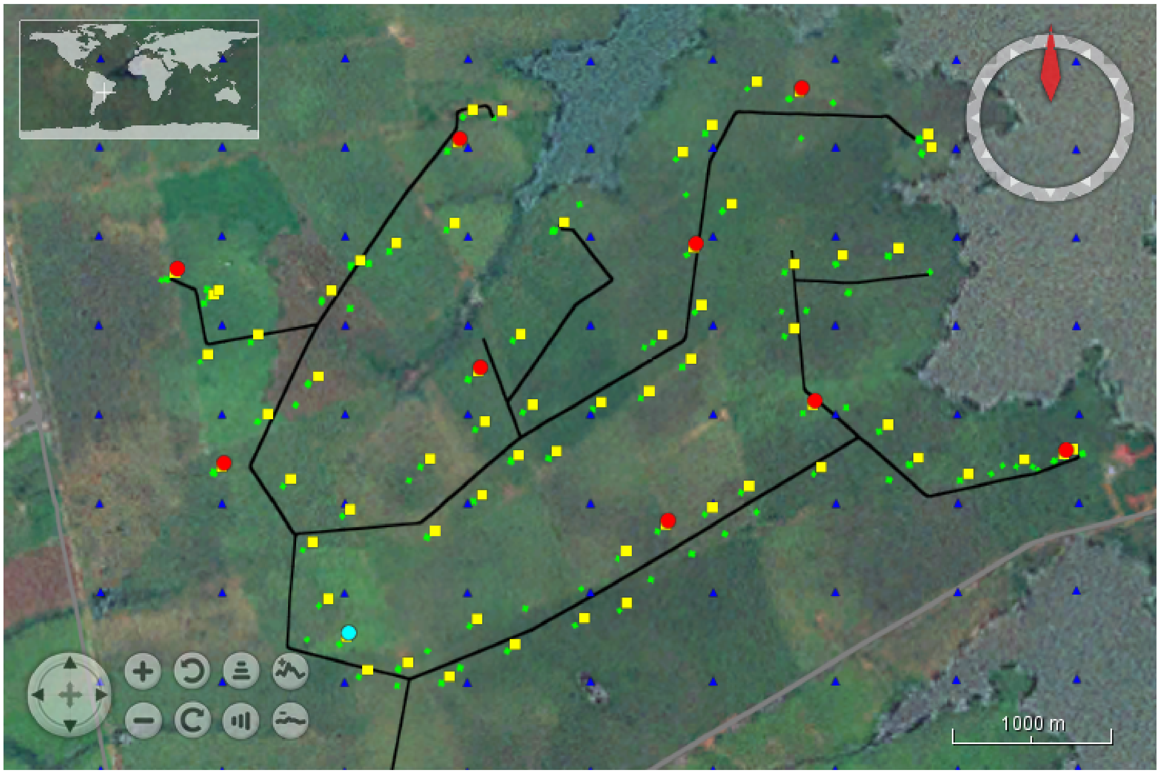


Figure 4.1. DER agent locations selected from preprocessing for the grid connected system

The analysis can be performed for number of cycles to get more accurate results. Equation 4.5 and equation 4.6 shows the complete probability matrix and corresponding probability matrix respectively after one complete cycle.

$$\begin{matrix} 0.001 & 0.001 & 0.001 & 0.001 & 0.001 & 0.001 & 0.001 & 0.001 & 0.001 & 0.001 \\ 0.001 & 0.001 & 0.001 & 0.001 & 0.001 & 0.001 & 0.001 & 0.001 & 0.001 & 0.001 \\ 2.5872 & 1.9153 & 1.9869 & 0.001 & 2.2523 & 1.8626 & 1.8283 & 1.0848 & 1.306 & 0.001 \\ 3.2283 & 2.5377 & 2.6297 & 2.6542 & 2.8704 & 2.5365 & 2.5169 & 1.3259 & 1.5719 & 1.758 \\ 6.0773 & 5.4486 & 5.5257 & 5.6019 & 5.7898 & 5.4011 & 5.3654 & 4.6251 & 4.8374 & 4.6632 \end{matrix} \tag{4.5}$$

$$\begin{matrix} 0.0001 & 0.0001 & 0.0001 & 0.0001 & 0.0001 & 0.0001 & 0.0001 & 0.0001 & 0.0001 & 0.0001 \\ 0.0001 & 0.0001 & 0.0001 & 0.0001 & 0.0001 & 0.0001 & 0.0001 & 0.0001 & 0.0001 & 0.0001 \\ 0.0282 & 0.0209 & 0.0217 & 0.0001 & 0.0246 & 0.0203 & 0.02 & 0.0119 & 0.0143 & 0.0001 \\ 0.0352 & 0.0277 & 0.0287 & 0.029 & 0.0313 & 0.0277 & 0.0275 & 0.0145 & 0.0172 & 0.0192 \\ 0.0662 & 0.0594 & 0.0602 & 0.0611 & 0.0631 & 0.0589 & 0.0585 & 0.0504 & 0.0527 & 0.0508 \end{matrix} \tag{4.6}$$

Equation 4.7 to equation 4.10 shows the similar results analyzed assuming the system is disconnected from the main grid and solely depend on the DERs. Figure 4.2 shows the corresponding DER locations under consideration by the multi agent system. Table 4.3 and table 4.4 show the locations and the considered capacities in tabular form.

$$\begin{matrix} 0.001 & 0.001 & 0.001 & 0.001 & 0.001 & 0.001 & 0.001 & 0.001 & 0.001 & 0.001 \\ 0.001 & 0.001 & 0.001 & 0.001 & 0.001 & 0.001 & 0.001 & 0.001 & 0.001 & 0.001 \\ 2.1238 & 2.5259 & 1.8042 & 0.001 & 0.001 & 0.001 & 0.001 & 0.001 & 0.001 & 0.001 \\ 2.8978 & 3.3224 & 0.001 & 0.001 & 0.001 & 0.001 & 0.001 & 0.001 & 0.001 & 0.001 \\ 5.1347 & 5.4702 & 0.001 & 0.001 & 0.001 & 0.001 & 0.001 & 0.001 & 0.001 & 0.001 \end{matrix} \tag{4.7}$$

$$\begin{matrix} 0.0001 & 0.0001 & 0.0001 & 0.0001 & 0.0001 & 0.0001 & 0.0001 & 0.0001 & 0.0001 & 0.0001 \\ 0.0001 & 0.0001 & 0.0001 & 0.0001 & 0.0001 & 0.0001 & 0.0001 & 0.0001 & 0.0001 & 0.0001 \\ 0.0911 & 0.1084 & 0.0774 & 0.0001 & 0.0001 & 0.0001 & 0.0001 & 0.0001 & 0.0001 & 0.0001 \\ 0.1243 & 0.1425 & 0.0001 & 0.0001 & 0.0001 & 0.0001 & 0.0001 & 0.0001 & 0.0001 & 0.0001 \\ 0.2202 & 0.2346 & 0.0001 & 0.0001 & 0.0001 & 0.0001 & 0.0001 & 0.0001 & 0.0001 & 0.0001 \end{matrix} \tag{4.8}$$

Table 4.3
Geographical coordinates considered by DER agents for the placement of DERs after the preprocessing

Geographical coordinate considered by DER agents (latitude, longitude, 0.0)
(-51.28986402460718, -20.41525116757932, 0.0)
(-51.276006825326, -20.41429158169525, 0.0)
(-51.30272668321311, -20.41902353196104, 0.0)
(-51.29832888779615, -20.42861192912458, 0.0)
(-51.26836980242612, -20.43123110983011, 0.0)
(-51.31595079247784, -20.42258244202963, 0.0)
(-51.28359657419744, -20.42459488153984, 0.0)
(-51.3119363457016, -20.43253886948136, 0.0)
(-51.28822327447352, -20.43403081824382, 0.0)
(-51.30759066306975, -20.44257260229675, 0.0)

$$\begin{array}{cccccccccc}
0.001 & 0.001 & 0.001 & 0.001 & 0.001 & 0.001 & 0.001 & 0.001 & 0.001 & 0.001 \\
0.001 & 0.001 & 0.001 & 0.001 & 0.001 & 0.001 & 0.001 & 0.001 & 0.001 & 0.001 \\
2.1238 & 2.5259 & 1.8042 & 1.4649 & 2.1921 & 1.8021 & 1.8843 & 1.0201 & 1.2972 & 0.001 \\
2.8978 & 3.3224 & 2.6075 & 2.2539 & 2.9935 & 2.6467 & 2.6693 & 1.8042 & 2.0668 & 0.001 \\
5.1347 & 5.4702 & 4.8537 & 4.53 & 5.1877 & 4.8212 & 4.7828 & 4.0173 & 4.2582 & 0.001
\end{array} \tag{4.9}$$

$$\begin{array}{cccccccccc}
0.0001 & 0.0001 & 0.0001 & 0.0001 & 0.0001 & 0.0001 & 0.0001 & 0.0001 & 0.0001 & 0.0001 \\
0.0001 & 0.0001 & 0.0001 & 0.0001 & 0.0001 & 0.0001 & 0.0001 & 0.0001 & 0.0001 & 0.0001 \\
0.0258 & 0.0307 & 0.0219 & 0.0178 & 0.0266 & 0.0219 & 0.0229 & 0.0124 & 0.0158 & 0.0001 \\
0.0352 & 0.0403 & 0.0317 & 0.0274 & 0.0364 & 0.0321 & 0.0324 & 0.0219 & 0.0251 & 0.0001 \\
0.0623 & 0.0664 & 0.0589 & 0.055 & 0.063 & 0.0585 & 0.0581 & 0.0488 & 0.0517 & 0.0001
\end{array} \tag{4.10}$$

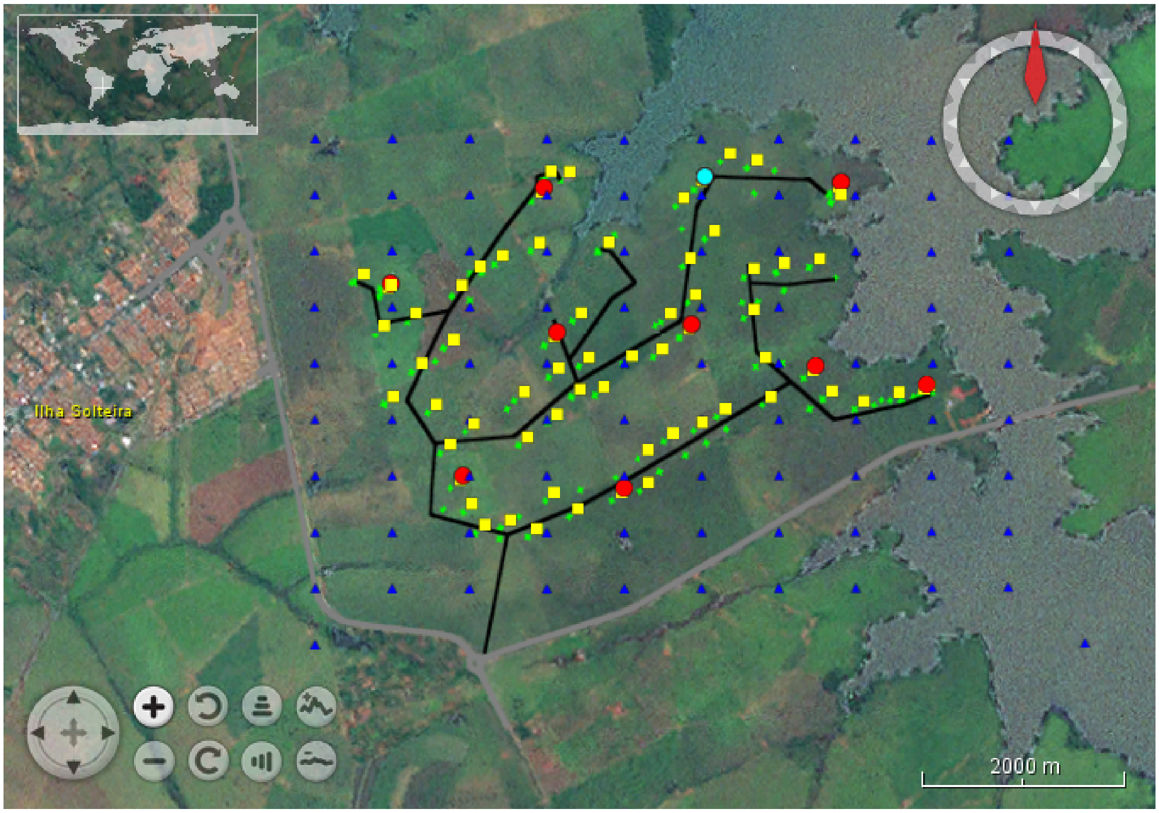


Figure 4.2. DER agent locations selected from preprocessing for non grid connected system

Table 4.4
Capacities considered by DER agents for the DERs after the preprocessing

Capacities considered by DER agents (kW)
25.0
100.0
250.0
500.0
1000.0

4.2.1 Optimal Location and Capacity selection

the optimization criteria and the selection procedure was described in section 3.2.1 and section 3.2.2. The tool supports four deferent approaches to generate load profiles. In each of these approach DER placement can be analyzed for user defined capacity set or capacity set generated according to the GIS information.

Sections below present the results for each approach.

4.2.1.1. With random load profiles

The random load profile with minimum value of 0.2 kW and the maximum value of 8.6 kW was considered.

Equation 4.11 shows the final probability matrix for the user define capacity sets with the values {25, 100, 200, 250, 300, 500, 1000} kW. Figure 4.3 shows the corresponding location selection. The final outcome of the simulation is :

- Best Location:
  - ‘ Longitude: -51.30298386147196
  - Latitude: -20.44290228538016
- Best Capacity: 250 kW
- DER type: SolarPV

$$
\begin{array}{cccccccccc}
0.0001 & 0.0001 & 0.0001 & 0.0001 & 0.0001 & 0.0001 & 0.0001 & 0.0001 & 0.0001 & 0.0001 \\
0.0001 & 0.0001 & 0.0001 & 0.0001 & 0.0001 & 0.0001 & 0.0001 & 0.0001 & 0.0001 & 0.0001 \\
0.0001 & 0.0001 & 0.0001 & 0.0001 & 0.0001 & 0.0001 & 0.0001 & 0.0001 & 0.0001 & 0.0001 \\
0.0001 & 0.0001 & 0.0001 & 0.0001 & 0.0001 & 0.0001 & 0.0001 & 0.0001 & 0.0001 & 0.0001 \\
0.0001 & 0.0001 & 0.0001 & 0.0001 & 0.0001 & 0.0001 & 0.0001 & 0.0001 & 0.0001 & 0.0001 \\
0.0001 & 0.0001 & 0.0001 & 0.0001 & 0.0001 & 0.0001 & 0.0001 & 0.0001 & 0.0001 & 0.0001 \\
0.1075 & 0.1246 & 0.0883 & 0.1092 & 0.0806 & 0.1309 & 0.0661 & 0.1312 & 0.0955 & 0.0635
\end{array}
\tag{4.11}
$$

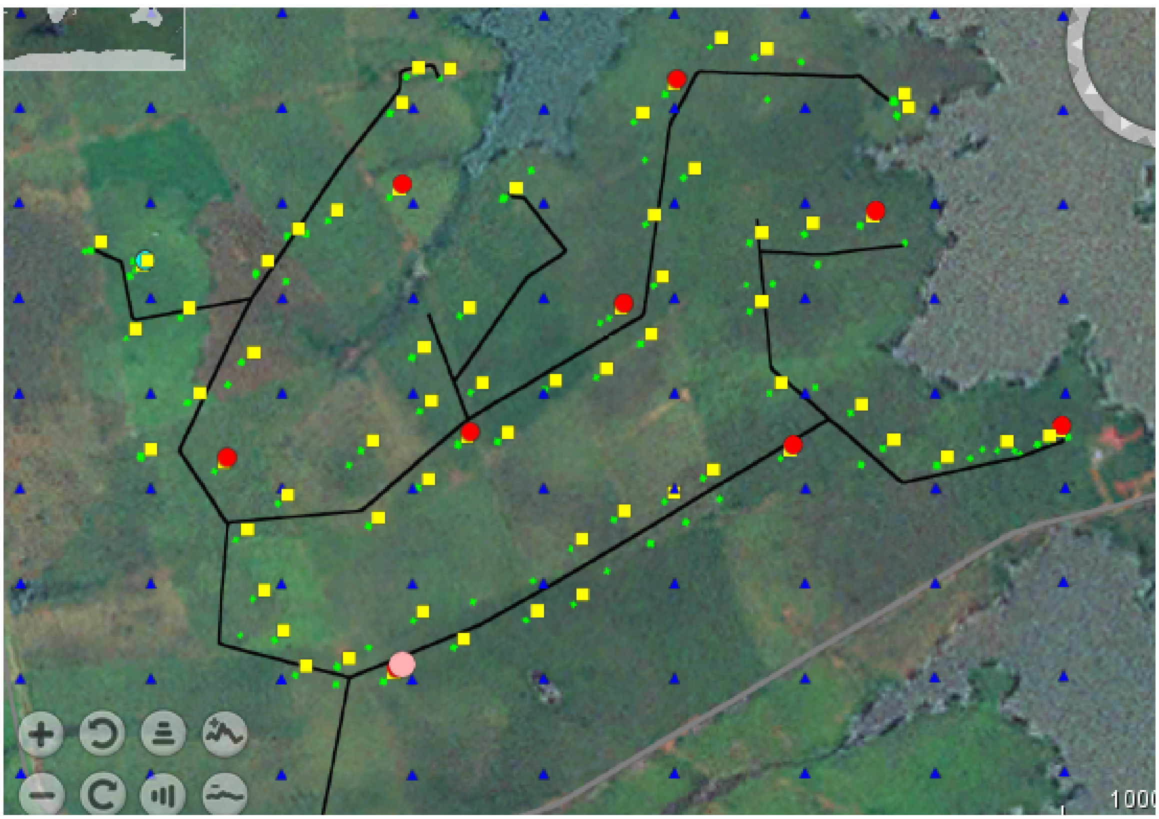


Figure 4.3. DER agent locations selected for user defined capacity set and random load profiles

Equation 4.12 shows the final probability matrix for the user define capacity sets with the values {25, 100, 200, 250, 300, 500, 1000} kW. Figure 4.4 shows the corresponding location selection. The final outcome of the simulation is :

- Best Location:
  - ‘ Longitude: -51.29931105706441
  - Latitude: -20.44123651358428
- Best Capacity: 264 kW
- DER type: SolarPV

$$\begin{matrix} 0.0001 & 0.0133 & 0.0131 & 0.0129 & 0.0001 & 0.0138 & 0.0133 & 0.0136 & 0.0137 & 0.0132 \\ 0.0127 & 0.0126 & 0.0249 & 0.0125 & 0.0126 & 0.0125 & 0.0125 & 0.0124 & 0.0124 & 0.0122 \\ 0.0133 & 0.0001 & 0.0134 & 0.013 & 0.0001 & 0.0136 & 0.013 & 0.0134 & 0.0137 & 0.0135 \\ 0.0125 & 0.0126 & 0.0125 & 0.0124 & 0.0126 & 0.0125 & 0.0127 & 0.0124 & 0.0124 & 0.0125 \\ 0.013 & 0.0129 & 0.0126 & 0.0132 & 0.0136 & 0.0128 & 0.0125 & 0.013 & 0.013 & 0.0127 \\ 0.0132 & 0.0127 & 0.0129 & 0.0129 & 0.014 & 0.0132 & 0.0125 & 0.0137 & 0.0135 & 0.013 \\ 0.0139 & 0.0135 & 0.0135 & 0.0134 & 0.014 & 0.0138 & 0.0133 & 0.0131 & 0.0135 & 0.0132 \\ 0.013 & 0.0127 & 0.0132 & 0.0137 & 0.0127 & 0.0135 & 0.0133 & 0.013 & 0.0133 & 0.0131 \end{matrix} \tag{4.12}$$

4.2.1.2. With survey based load profiles

Equation 4.13 shows the final probability matrix for the user define capacity sets with the values {25, 100, 200, 250, 300, 500, 1000} kW. Figure 4.5 shows the corresponding location selection. The final outcome of the simulation is :

- Best Location:

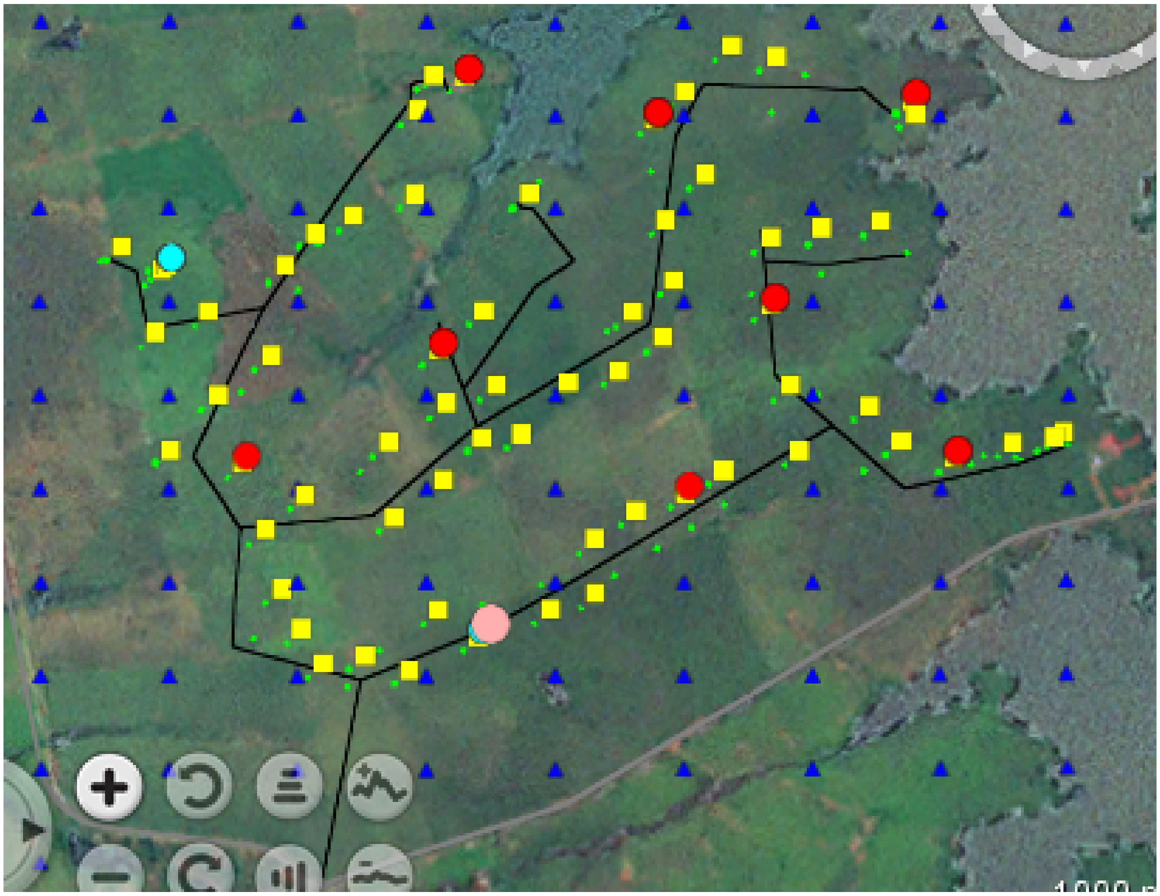


Figure 4.4. DER agent locations selected for user defined capacity set and random load profiles

  - ‘ Longitude: -51.3119363457016
  - Latitude: -20.43253886948136

- Best Capacity: 200 kW
- DER type: SolarPV

$$
\begin{matrix}
0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\
0.0215 & 0.0156 & 0.0162 & 0 & 0.0153 & 0.0185 & 0.0149 & 0.0085 & 0 & 0 \\
0.0223 & 0.0163 & 0 & 0.018 & 0.0162 & 0.0192 & 0.0155 & 0 & 0.0115 & 0 \\
0.0228 & 0.016 & 0.0187 & 0.0193 & 0.0172 & 0.0202 & 0.0153 & 0.011 & 0.0128 & 0 \\
0.0261 & 0.0258 & 0.0262 & 0.0259 & 0.0237 & 0.0228 & 0.0251 & 0.0184 & 0.0194 & 0 \\
0.0542 & 0.0479 & 0.0465 & 0.0459 & 0.0344 & 0.0512 & 0.0472 & 0.0387 & 0.0394 & 0
\end{matrix}
\tag{4.13}
$$

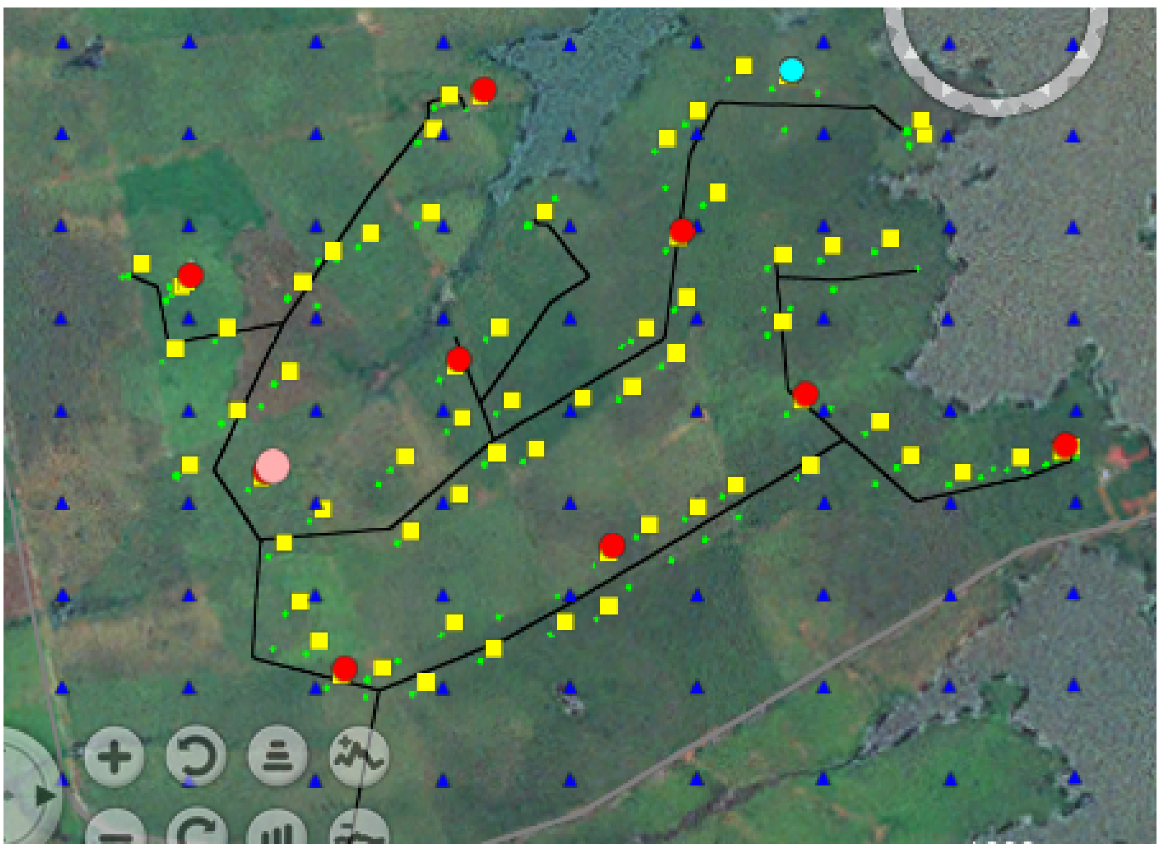


Figure 4.5. DER agent locations selected for user defined capacity set and survey based load profiles

Equation 4.14 shows the final probability matrix for the auto generated capacity sets with the values {21.46 164.40 32.38 245.42 142.37 } kW. Figure 4.6 shows the corresponding location selection. The final outcome of the simulation is :

- Best Location:
  - ‘ Longitude: -51.3119363457016
  - Latitude: -20.43253886948136
- Best Capacity: 245 kW
- DER type: SolarPV

$$\begin{matrix} 0.0001 & 0.0001 & 0.0001 & 0.0001 & 0.0001 & 0.0001 & 0.0001 & 0.0001 & 0.0001 & 0.0001 \\ 0.0001 & 0.0001 & 0.0001 & 0.0001 & 0.0001 & 0.0001 & 0.0001 & 0.0001 & 0.0001 & 0.0001 \\ 0.0001 & 0.0001 & 0.0001 & 0.0001 & 0.0001 & 0.0001 & 0.0001 & 0.0001 & 0.0001 & 0.0001 \\ 0.1532 & 0.1138 & 0.1181 & 0.1228 & 0.1343 & 0.1106 & 0.1085 & 0.0631 & 0.0736 & 0.0001 \\ 0.0001 & 0.0001 & 0.0001 & 0.0001 & 0.0001 & 0.0001 & 0.0001 & 0.0001 & 0.0001 & 0.0001 \end{matrix} \tag{4.14}$$

4.2.1.3. With load profiles generated from the behavior

The load profiles of the customers were generated based on their usage patterns. The usage patterns specifies the usage time or time periods of different appliances. The data can be collected from a sample population in the area under investigation. A randomness of the profile was created by slightly changing the usage time of the appliances for each customer.

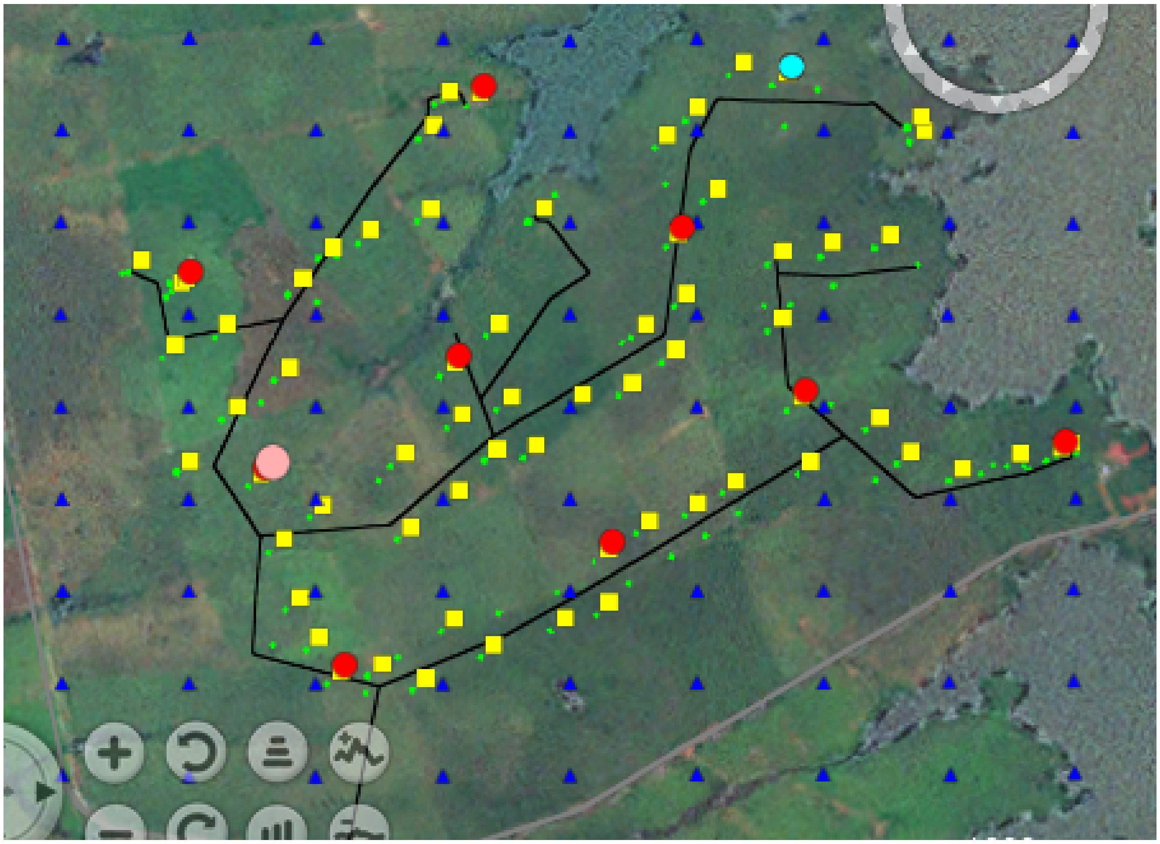


Figure 4.6. DER agent locations selected for user defined capacity set and behavior based load profiles

Equation 4.15 shows the final probability matrix for the user define capacity sets with the values {25, 100, 200, 250, 300, 500, 1000} kW. Figure 4.7 shows the corresponding location selection. The final outcome of the simulation is :

- Best Location:
  - ‘ Longitude: -51.3119363457016
  - Latitude: -20.43253886948136
- Best Capacity: 250 kW
- DER type: SolarPV

$$
\begin{matrix}
0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\
0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\
0.0233 & 0.0171 & 0 & 0 & 0.0201 & 0.0166 & 0.0162 & 0 & 0 & 0 \\
0.0236 & 0.018 & 0 & 0.0193 & 0.0201 & 0 & 0 & 0.0102 & 0.0123 & 0 \\
0.0256 & 0.0176 & 0.0186 & 0.0208 & 0.0225 & 0.0189 & 0.0168 & 0.0102 & 0.0137 & 0 \\
0.0337 & 0.0273 & 0.028 & 0.0238 & 0.0267 & 0.0269 & 0.0212 & 0.0196 & 0.0164 & 0 \\
0.0466 & 0.0426 & 0.0517 & 0.0524 & 0.054 & 0.0393 & 0.041 & 0.0434 & 0.0454 & 0
\end{matrix}
\tag{4.15}
$$

Equation 4.16 shows the final probability matrix for the auto generated capacity sets with the values {19.95, 152.61, 261.93, 2.75, 60.17, 33.96, 221.12, 281.28} kW. Figure 4.8 shows the corresponding location selection. The final outcome of the simulation is :

- Best Location:
    - ‘ Longitude: -51.30298386147196
    - Latitude: -20.44290228538016
- Best Capacity: 221.12 kW
- DER type: SolarPV

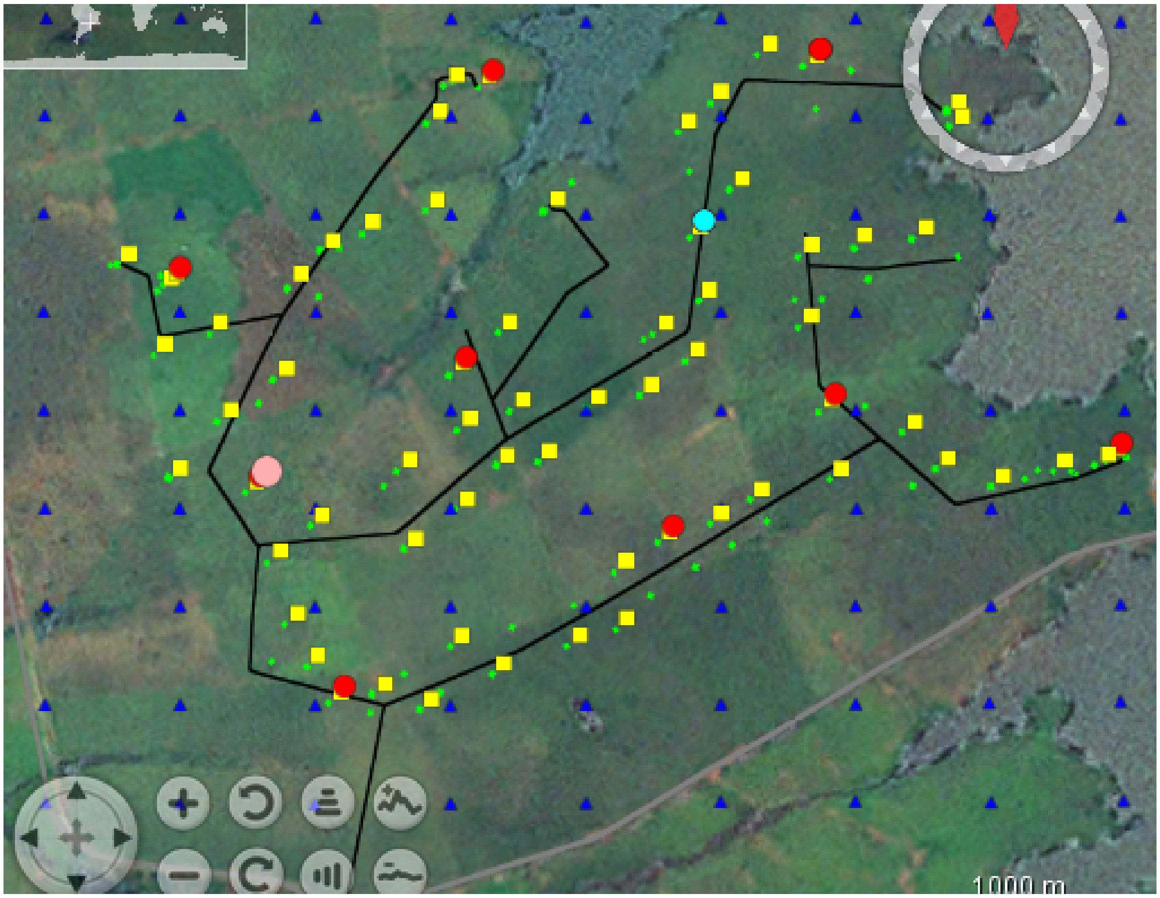


Figure 4.7. DER agent locations selected for user defined capacity set and behavior based load profiles

$$
\begin{matrix}
0.0001 & 0.0001 & 0.0001 & 0.0001 & 0.0001 & 0.0001 & 0.0001 & 0.0001 & 0.0001 & 0.0001 \\
0.0001 & 0.0001 & 0.0001 & 0.0001 & 0.0001 & 0.0001 & 0.0001 & 0.0001 & 0.0001 & 0.0001 \\
0.0578 & 0.0577 & 0.0365 & 0.045 & 0.0326 & 0.053 & 0.0278 & 0.0256 & 0.0481 & 0.0422 \\
0.0001 & 0.0001 & 0.0001 & 0.0001 & 0.0001 & 0.0001 & 0.0001 & 0.0001 & 0.0001 & 0.0001 \\
0.0001 & 0.0001 & 0.0001 & 0.0001 & 0.0001 & 0.0001 & 0.0001 & 0.0001 & 0.0001 & 0.0001 \\
0.0001 & 0.0001 & 0.0001 & 0.0001 & 0.0001 & 0.0001 & 0.0001 & 0.0001 & 0.0001 & 0.0001 \\
0.0001 & 0.0552 & 0.0363 & 0.0455 & 0.0001 & 0.0001 & 0.0253 & 0.0258 & 0.0001 & 0.0001 \\
0.0593 & 0.0592 & 0.0369 & 0.0455 & 0.0341 & 0.0503 & 0.0293 & 0.0268 & 0.0001 & 0.0437
\end{matrix}
\tag{4.16}
$$

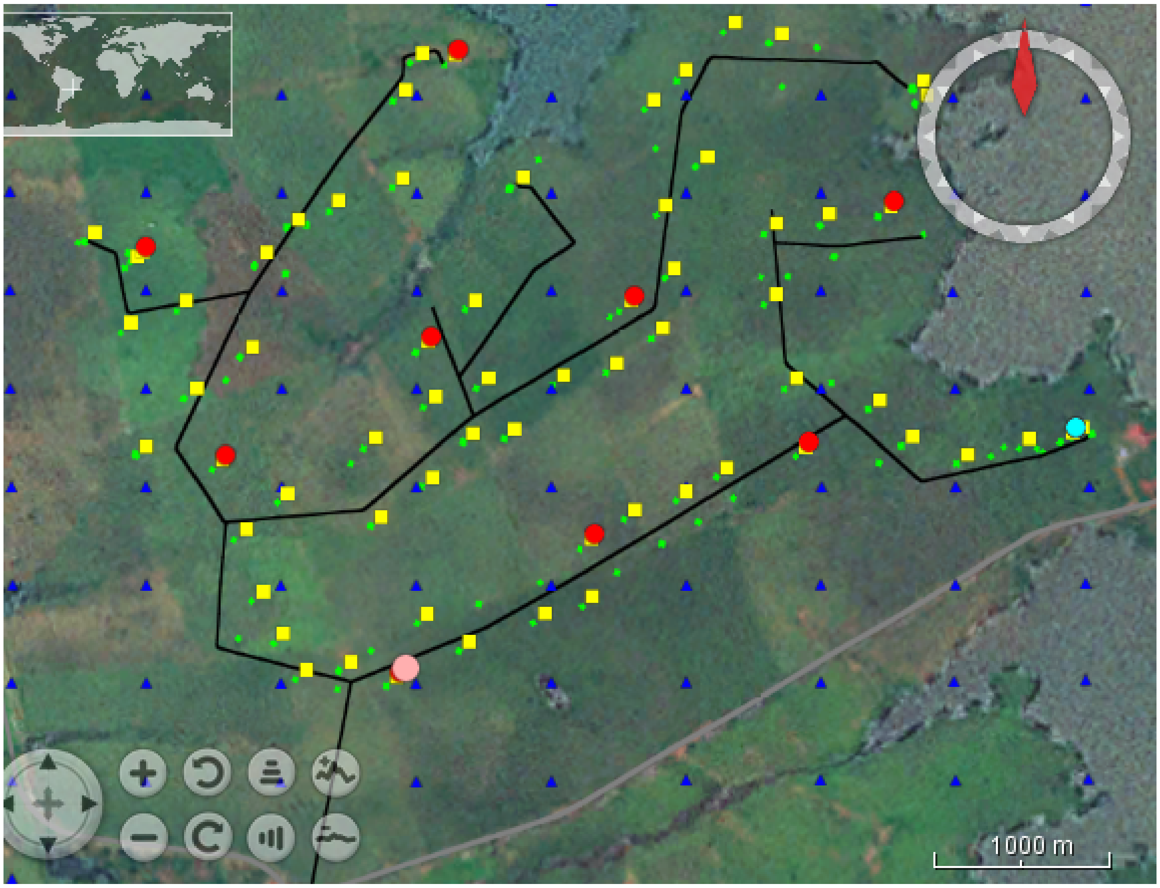


Figure 4.8. DER agent locations selected for user defined capacity set and behavior based load profiles

The number of simulations were performed to verify the consistency of the methodology. Table 4.5 shows the sample sets of locations, capacities and DER types obtained for various scenarios. Figure 4.9 shows the locations in the GIS map with the power system and the load points. Figure 4.10 shows the number of occurrence for each locations for the set of scenarios.

Table 4.5
Location, capacity and DER type table for different scenarios

Load profile type	Configuration		Result		Description
	Num Locations / Num Capacities	DER Type	DER Capacity (kW)	DER location (Longitude, Latitude)	
Random	5/7	Solar PV	1000.00	(-51.30141341521276, -20.42685903000516)	User defined capacity set
Random	5/9	Solar PV	1000.00	(-51.30141341521276, -20.42685903000516)	User defined capacity set
Random	5/11	Solar PV	225.00	(-51.30257573624282, -20.4147649769593)	User defined capacity set
Random	5/13	Solar PV	225.00	(-51.30144276595351, -20.43988538302851)	User defined capacity set
Random	5/5	Solar PV	250.00	(-51.31622190250081, -20.42281384575344)	User defined capacity set
Random	10/5	Solar PV	250.00	(-51.3119363457016, -20.43253886948136)	User defined capacity set
Random	15/5	Solar PV	250.00	(-51.30759066306975, -20.44257260229675)	User defined capacity set
Behaviour	10/8	Solar PV	221.12	(-51.30298386147196, -20.44290228538016)	Auto generated capacity set
Behaviour	10/8	Solar PV	250.00	(-51.29084991541184, -20.43492651154567)	User defined capacity set
Behaviour	10/8	Solar PV	234.61	(-51.29307061953225, -20.4363150712377)	Auto generated capacity set, 50 initial steps
survay based	10/8	Solar PV	245	(-51.3119363457016, -20.43253886948136)	Auto generated capacity set
survay based	10/8	Solar PV	200	(-51.3119363457016, -20.43253886948136)	Auto generated capacity set

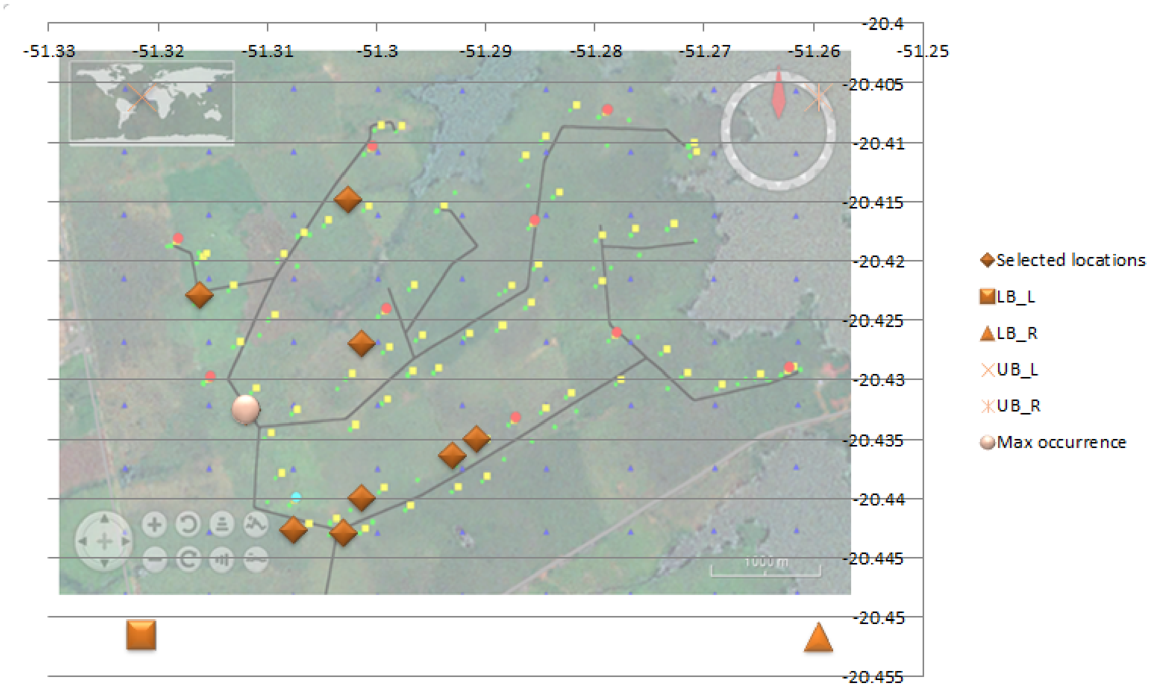


Figure 4.9. DER agent locations selected for the scenarios presented in table 4.5

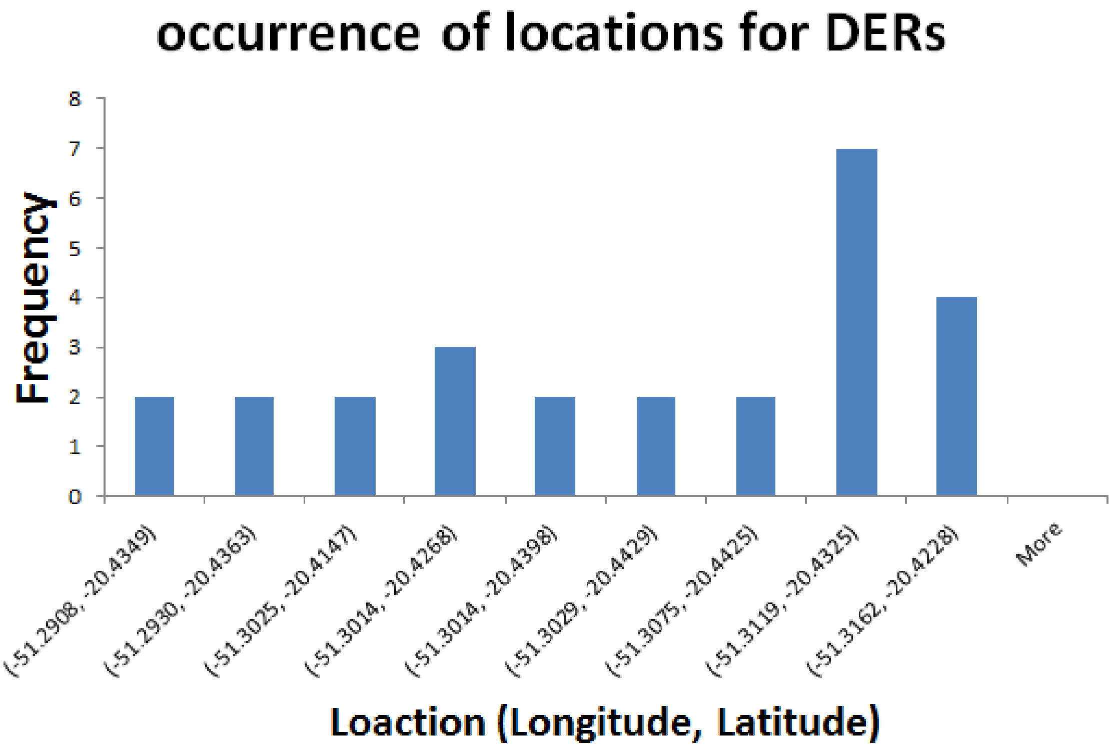


Figure 4.10. Number of occurrences for each selected location

4.2.1.4. Validation of behavior based load profile generation

The population was divided in to different categories based on occupation. Five categories were identified for the Estrella da Ilha population. The occupations include: farming vegetables, farming animals, farming cows for milk, normal residence, residence with low income. Monthly consumption of different households are available form January 2013 to November 2015. Several households were picked randomly in order to cover each group and validate the behavior based load profile. Table 4.6 shows the selected lots in each category.

Simulations were run over the span of two years from January 2013 to December 2014. Monthly consumptions were calculated from the load profiles generated by the simulation. Simulation generate consumption data with one hour

Table 4.6
Selected lots to validate behavior based load profile

Category name (occupations)	Category number	Lot numbers
Farming vegetables	4080	172, 175, 180, 131
Farming cows for milk	4169	177, 186, 200, 87
Farming animals	4011	126, 159
Normal residence	9101	57, 105
Residence with low income	9111	

intervals. Figures 4.11 to 4.14 show the plots of actual and simulated monthly consumption for selected lots in different categories. Table 4.7 shows the corresponding correlation factors.

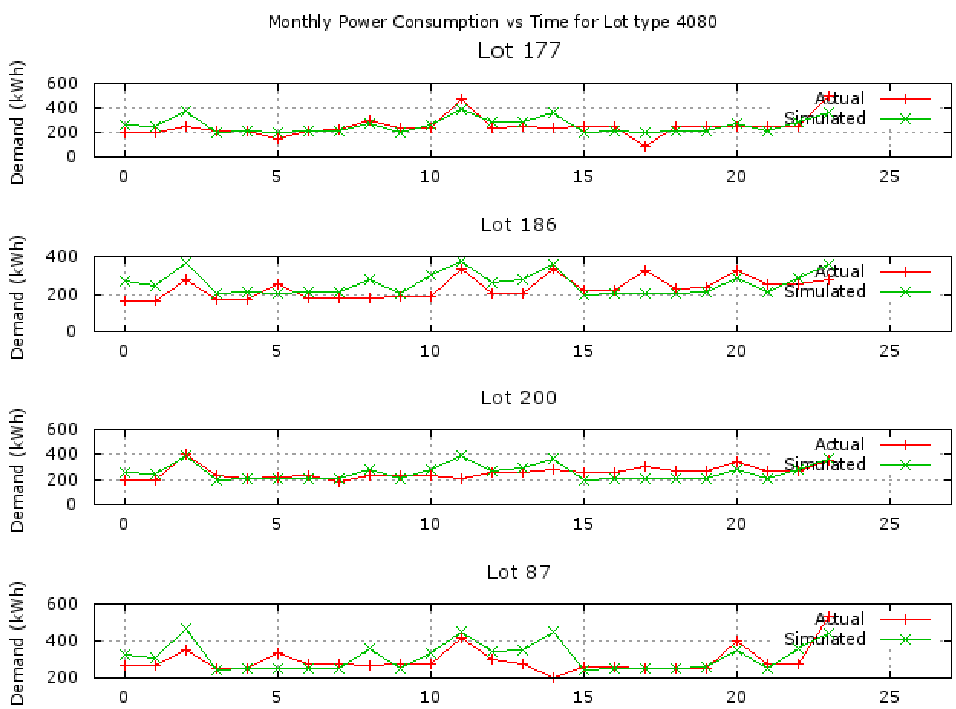


Figure 4.11. Actual and simulated monthly energy consumption for lot type 4080

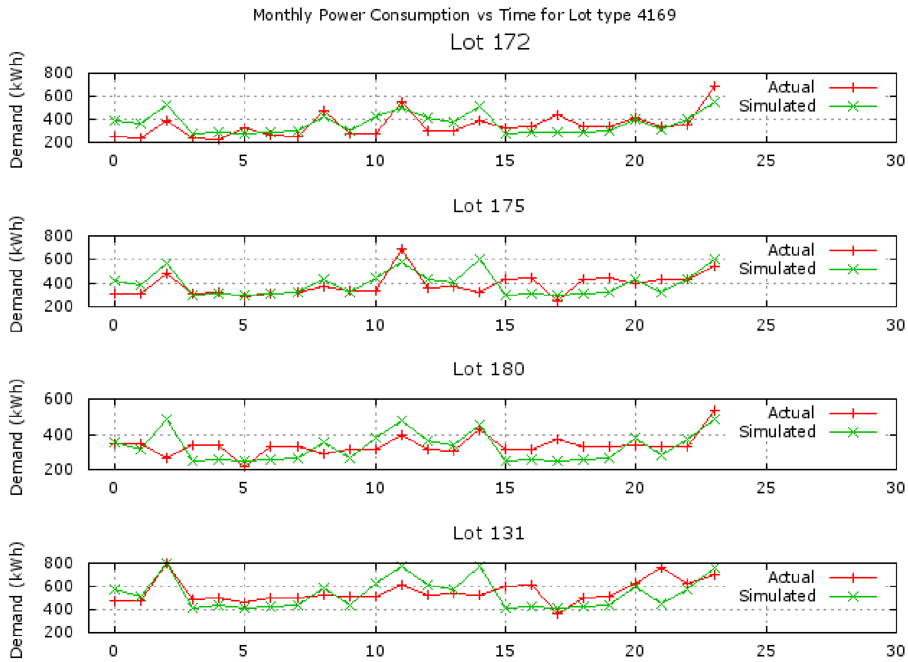


Figure 4.12. Actual and simulated monthly energy consumption for lot type 4169

Figure 4.13. Actual and simulated monthly energy consumption for lot type 4011

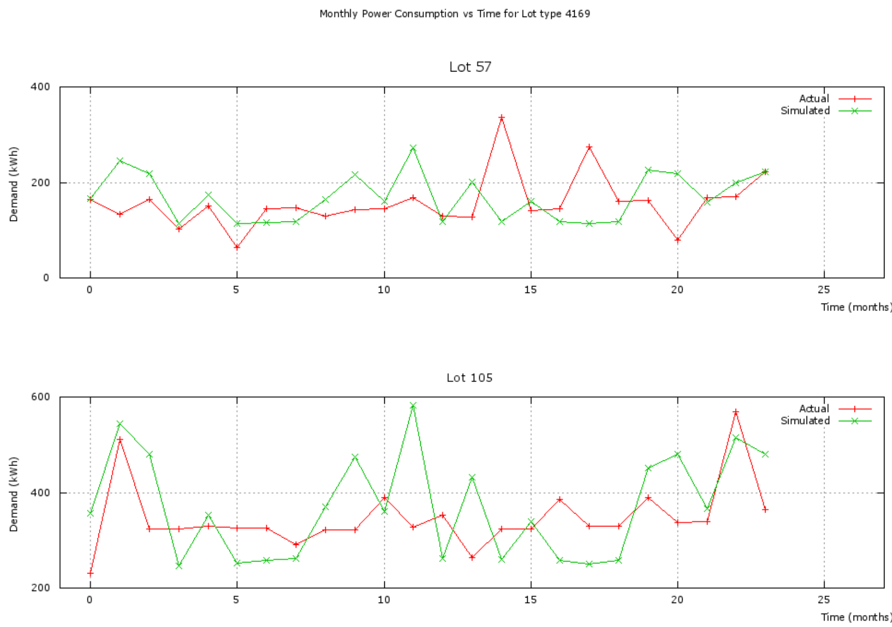


Figure 4.14. Actual and simulated monthly energy consumption for lot type 9101

Table 4.7
Correlation between actual and simulated monthly consumption data

Category number	Lot Number	correlation
4080	172	0.633
	175	0.515
	180	0.462
	131	0.483
4169	177	0.642
	186	0.504
	200	0.451
	87	0.502
4011	126	0.532
	159	0.419
9101	57	0.402
	105	0.433

Since the only data available was the monthly consumption, actual daily consumptions were calculated from the monthly consumption (assuming uniform pattern of consumption in each day during the month). Hourly consumption data was derived from the calculated daily values. The model presented by the Roberts et al. (2014) was used to derive the hourly consumption data. Roberts et al. (2014) presented the electricity usage patterns of different regions in Brazil. The modeled network is located in central-west region and the corresponding average daily load curve is given in figure 4.15.

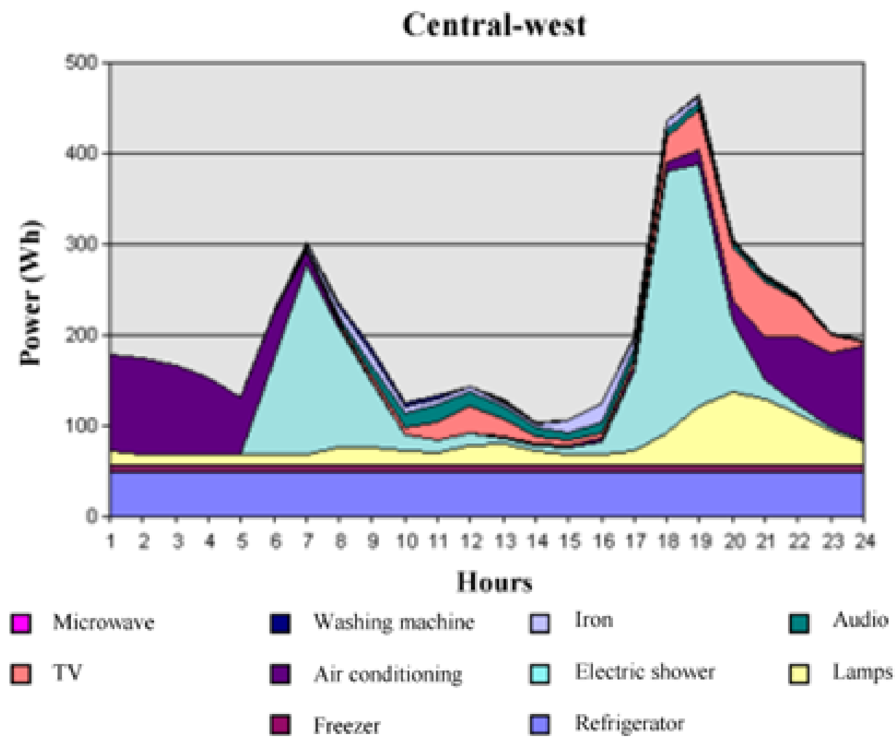


Figure 4.15. Residential sector average daily load curve in central-west Brazil (Roberts et al., 2014)

In the model presented, we can identify the average demand and the variation from the average demand in a given time. For example if the average demand of the day is equal to $P_{avg,day}$ and consumption at time t_i is equal to P_{t_i} according to the model presented by Roberts et al. (2014), equation 4.17 gives the variation of the demand at time t_i from the average daily demand.

$$P_{diff,t_i} = P_{t_i} - P_{avg,day} \tag{4.17}$$

Then equation 4.18 gives the ratio of variation in demand to the average daily demand.

$$P_{r,t_i} = \frac{P_{diff,t_i}}{P_{avg,day}} \tag{4.18}$$

Applying this equation for the model presented in Roberts et al. (2014) for each hour will give you a vector of ratios such that:

$$P_R = \begin{bmatrix} P_{r,t_1} & P_{r,t_2} & \cdots & P_{r,t_i} & \cdots & P_{r,t_{24}} \end{bmatrix}$$

So with the daily average calculated from the actual data ($P_{avg,act}$), we can calculate the hourly consumption as:

$$P_{act,t_i} = P_{avg,act} + P_{avg,act} \times P_{r,t_i} \tag{4.19}$$

These calculated hourly consumptions were compared with the simulated results from the behavior model to validate the behavior model. Figures 4.16 to 4.19 show the result obtained for two randomly picked lots in each lot type. The simulated results were plotted for three randomly picked days during a single month with the actual hourly consumption obtained for that month. Table 4.8 lists the correlation between simulated and actual demand profiles.

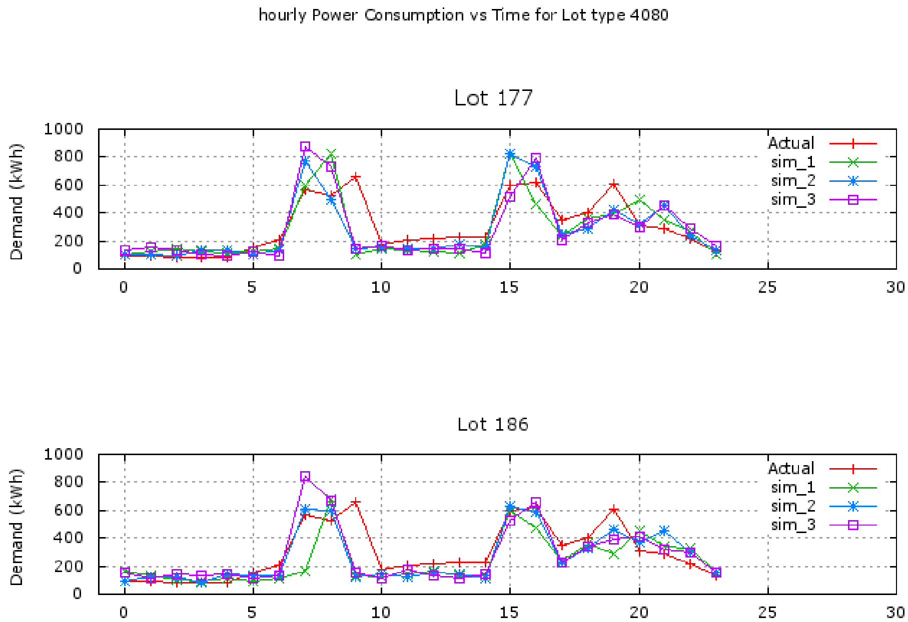


Figure 4.16. Actual and simulated hourly energy consumption for lot type 4080

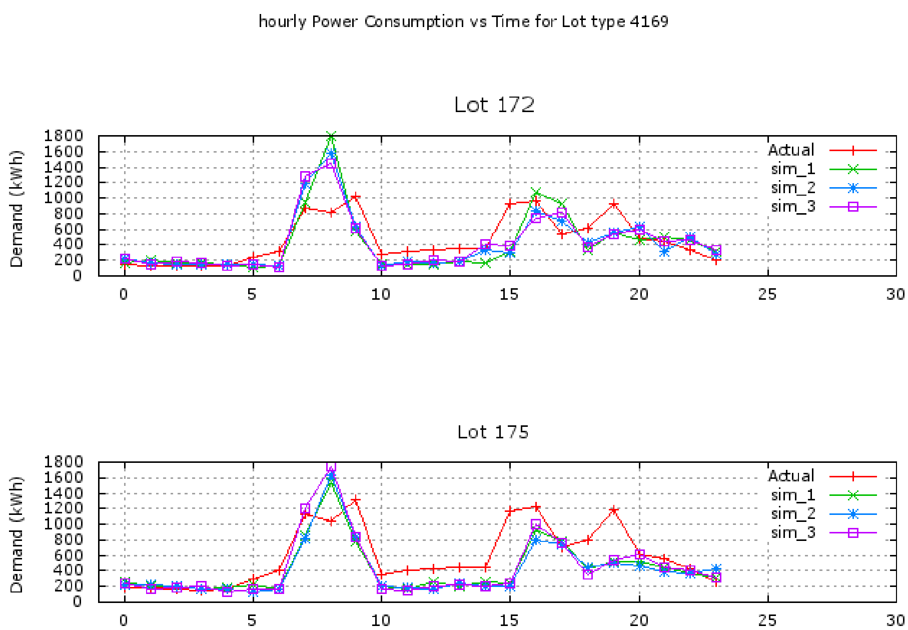


Figure 4.17. Actual and simulated hourly energy consumption for lot type 4169

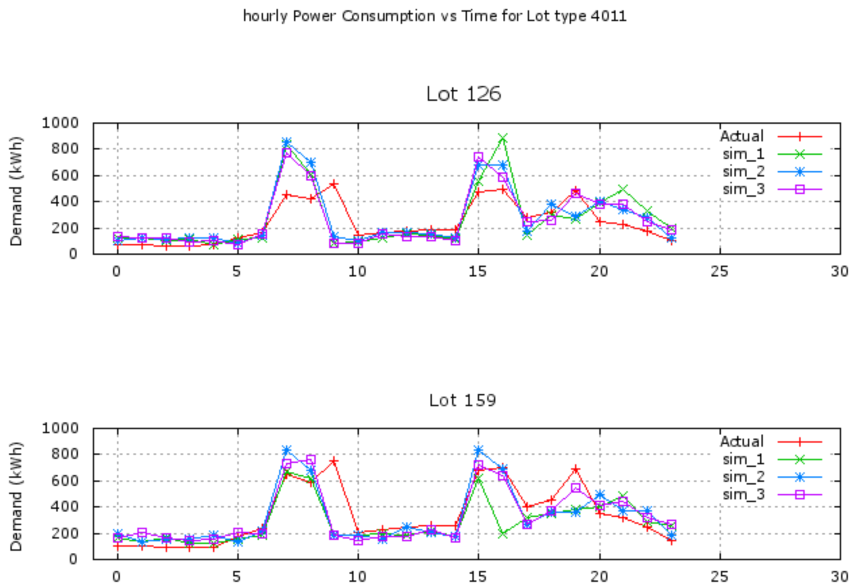


Figure 4.18. Actual and simulated hourly energy consumption for lot type 4011

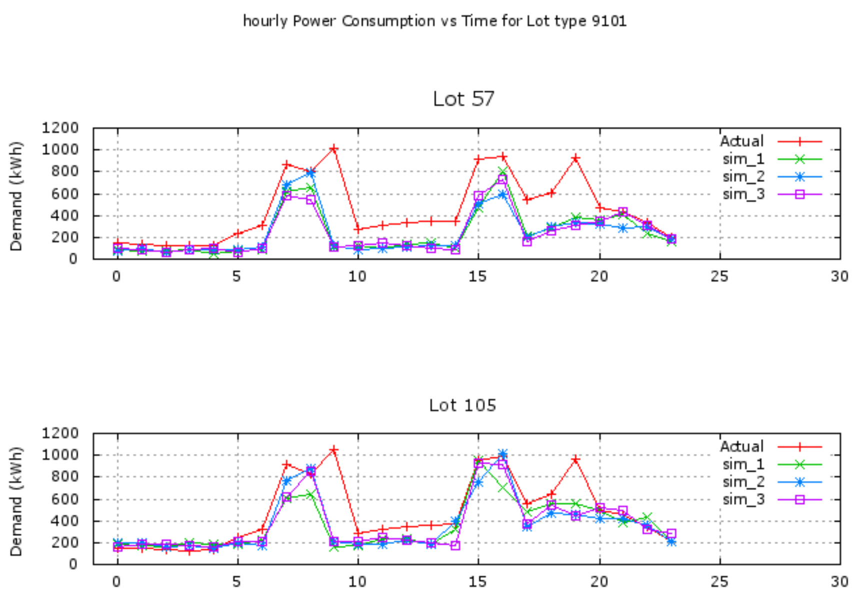


Figure 4.19. Actual and simulated hourly energy consumption for lot type 9101

Table 4.8
Correlation between actual and simulated daily consumption data

Category number	Lot Number	Simulation number	correlation
4080	177	1	0.697
		2	0.767
		3	0.730
	186	1	0.657
		2	0.769
		3	0.741
4169	172	1	0.698
		2	0.698
		3	0.702
	175	1	0.698
		2	0.662
		3	0.696
4011	126	1	0.669
		2	0.729
		3	0.743
	159	1	0.634
		2	0.736
		3	0.770
9101	57	1	0.759
		2	0.738
		3	0.727
	105	1	0.750
		2	0.765
		3	0.752

It can be seen from table 4.8 the correlation between actual hourly consumption and the simulated hourly consumption is between 65% and 77%. The table 4.7 shows that correlation between actual monthly consumption and simulated monthly consumption ranges from 40% to 65% . The model presented in this paper uses a conditional rule based system to generate the electricity consumption. The thesis doesn't focus on utilizing any advanced techniques as this is not the main objective. The conditional rule based system is sufficient enough to prove the concept of this thesis. The correlation can be improved by using advanced models that use fuzzy logic, AI, neural networks etc..

4.2.1.5. Reliability analysis

The main objective of the research is to use MAS to find the optimal location of the DER to increase the reliability of the distribution system. The location selected from the MAS is shown in figure 4.9 and its coordinates are equal to (-51.3075,-20.4325). This location is corresponds to "Terminal 128" in the power system model shown in 4.20. The size and the type of the DER selected is equal to 275kW PV.

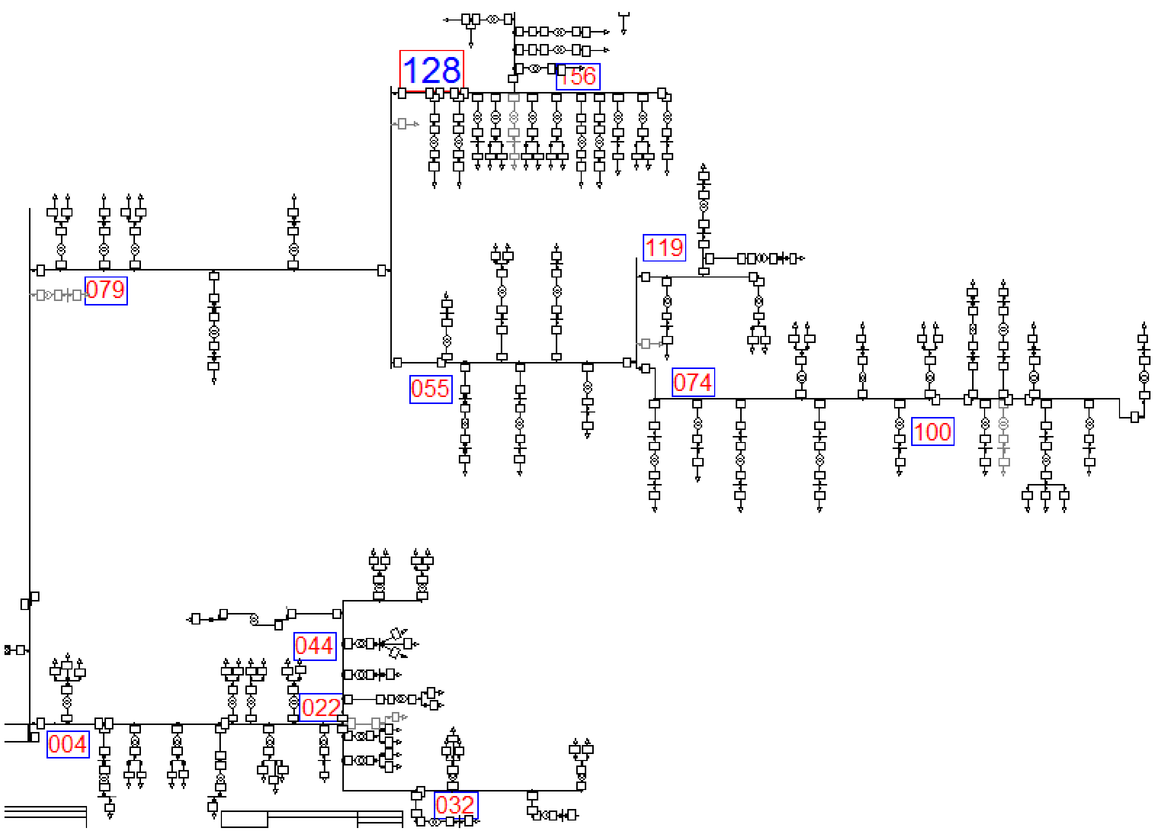


Figure 4.20. Randomly selected locations to perform reliability analysis

The number of reliability analyses were done by placing the DER with same type and the capacity in randomly selected locations in the network to verify that the location selected was optimal.Figure 4.20 shows the selected terminals for the DER placement in reliability test. Table 4.9 shows the results obtained by the reliability analysis test for single experiment. Output parameters are defined according to 1366-2001 - IEEE Guide for Electric Power Distribution Reliability Indices (IEEE, 2001):

- **SAIFI** : Indicates how often the average customer experiences a sustained interruption during the period specified.
- **SAIDI** : Indicates the total duration of interruption for the average customer during the period specified.
- **ASAI** : Represents the fraction of time that a customer is connected during the defined calculation period.
- **AENS** : Average amount of energy not supplied, for all customers.
- **ASIFI** : Is the equivalent of SAIFI but based on load.
- **ASIDI** : Is the equivalent of SAIDI but based on load.

The values of these varies highly depending on the configuration of the network and the technology used by different utility companies. Martin Kurtovich and Marzia Zafar (2016) and Ahmad and Hussein (2014) provide the reliability analysis of different electrical networks. According to Martin Kurtovich and Marzia Zafar (2016) SAIDI varies from 0.5 h/Ca to 12.5 h/Ca and SAIFI varies from 0.39 /Ca to 4/Ca for different cities in California.

Ten such experiments were done by changing the demand of the customer at each experiment. Analysis of variance (ANOVA) test was performed to identify the

Table 4.9
The results of reliability analysis

Terminal	SAIFI 1/Ca	SAIDI h/Ca	ASAI	AENS MWh/Ca	ASIFI 1/a	ASIDI h/a
79	0.406686	4.166856	0.999524	0.056142	0.393772	4.037716
128	0.390078	4.000781	0.999543	0.054246	0.380138	3.901376
156	0.545609	5.556094	0.999366	0.075252	0.531211	5.412107
119	0.521059	5.310587	0.999394	0.074414	0.525180	5.351798
74	0.510649	5.206495	0.999406	0.073557	0.519016	5.290158
100	0.627424	6.374241	0.999272	0.091290	0.646555	6.565547
4	0.427635	4.376354	0.999500	0.058523	0.410894	4.208937
44	0.616801	6.268007	0.999284	0.084885	0.600486	6.104860
22	0.521834	5.318338	0.999393	0.071472	0.504026	5.140259
32	0.644069	6.540687	0.999253	0.088201	0.624336	6.343361
55	0.408224	4.182236	0.999523	0.057169	0.401154	4.111535

significant of the selected location. Since the experiments only change the demand, the only parameters affected are the ASIFI, ASIDI and the AENS. Figure 4.21, 4.22 and 4.23 shows the mean and the variation of ASIFI, ASIDI and AENS respectively, when DER is placed at the selected locations shown in figure 4.20. Figures shows that, ASIFI, ASIDI and AENS are minimized when DER is placed at terminal 128.

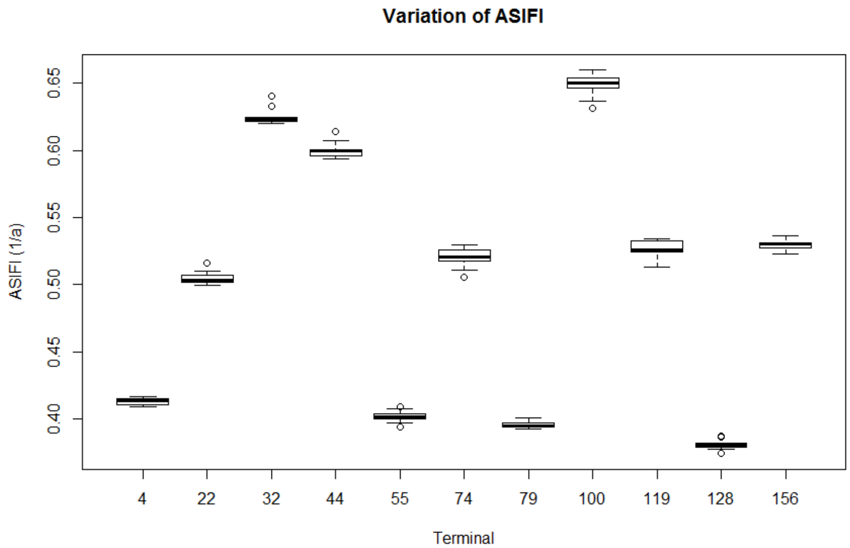


Figure 4.21. Variation of ASIFI when DER is placed at the selected locations

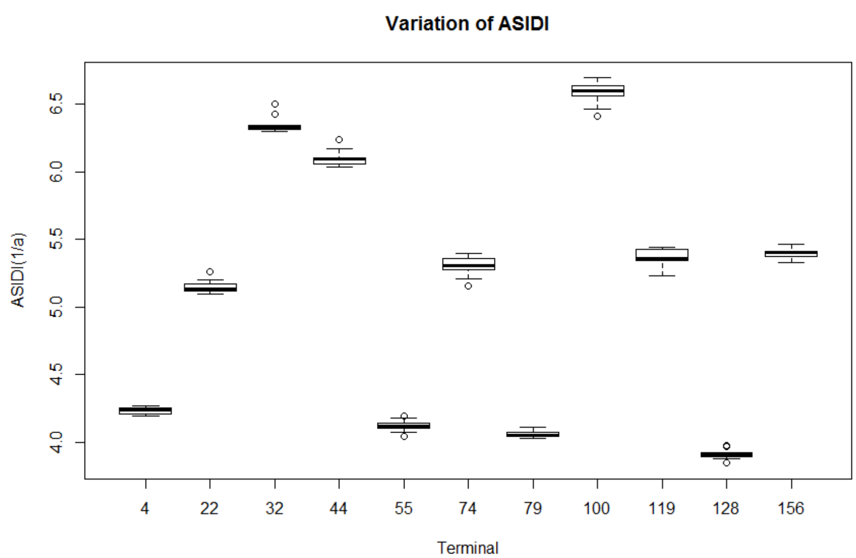


Figure 4.22. Variation of ASIDI when DER is placed at the selected locations

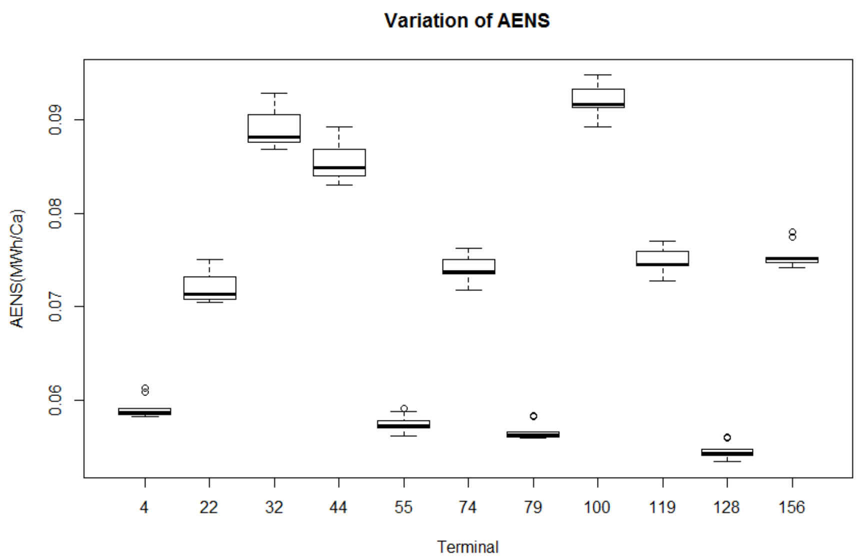


Figure 4.23. Variation of AENS when DER is placed at the selected locations

The significant of the results were analyzed using ANOVA test. The test were done to analyze the variation of ASIFI, ASIDI and AENS as they were the only parameters in reliability analysis affect by changing load. minimizing ASIFI, ASIDI and AENS will maximize the reliability. Following subsections provide an statistical analysis to show that the placing DER in the selected location minimizes ASIFI, ASIDI and AENS and hence maximizes the reliability.

4.2.1.5.1. Analysis of ASIFI

ASIFI, (Average System Interruption Frequency Index), indicates how often the average customer experiences a sustained interruption during the period specified. Figure 4.21 shows the variation of ASIFI. It can be seen that ASIFI is minimized when DER is placed at terminal 128. Following hypothesis were constructed to analyze the significant.

H_0 = There is no difference in mean ASIFI when DERs are placed in selected terminals

H_1 = There is a difference in mean ASIFI when DERs are placed in selected terminals

Statistical software R, was used to do the analysis. The result below shows the output of the ANOVA test

```
           Df  Sum Sq   Mean Sq   F  value   Pr(>F)
Exper       9  0.0005  0.00005     1.737      0.092 .
Term       10  0.9170  0.09170  3116.339   <2e-16 ***
Residuals  90  0.0026  0.00003
---
Signif. codes: 0  ***  0.001  **  0.01  *  0.05  .  0.1    1
```

The results shows that p-value for the variable Term (Terminal) is less than 0.05, which is the selected alpha level for 95% confidence interval. So we can reject the null hypothesis and we are 95% confidence that the the ASIFI will have different values depending on the selected location.

Dunnett multiple comparison was done to compare the ASIFI of other terminals with the selected terminal (Terminal 128).

```
         Simultaneous Tests for General Linear Hypotheses

     Multiple Comparisons of Means: Dunnett Contrasts

     Fit: aov(formula = ASIFI ~ Exper + Term, data = ASIFI_data)

     Linear Hypotheses:

                    Estimate  Std. Error t value Pr(>|t|)
       4 - 128 == 0 0.032394  0.002426  13.353  < 1e-07 ***
      22 - 128 == 0 0.124372  0.002426  51.267  < 1e-07 ***
      32 - 128 == 0 0.244448  0.002426 100.764  < 1e-07 ***
      44 - 128 == 0 0.219197  0.002426  90.355  < 1e-07 ***
      55 - 128 == 0 0.021271  0.002426   8.768  < 1e-07 ***
      74 - 128 == 0 0.139014  0.002426  57.303  < 1e-07 ***
      79 - 128 == 0 0.014731  0.002426   6.072 1.62e-07 ***
     100 - 128 == 0 0.267438  0.002426 110.240  < 1e-07 ***
     119 - 128 == 0 0.145048  0.002426  59.790  < 1e-07 ***
     156 - 128 == 0 0.149155  0.002426  61.483  < 1e-07 ***
     ---
Signif. codes: 0   ***   0.001   **   0.01   *   0.05   .   0.1        1
```

Dunnett multiple comparison compares ASIFI value when DER is at different terminals to ASIFI when DER is at 128. The results shows all the p-values are less than 0.05 which is our confidence level. This indicates that the ASIFI has significant different when placed in other terminals than terminal 128. The positive p-values at each comparison indicates that the minimum ASIFI value is produced when the DER is placed at terminal 128.

With these two tests we can conclude that when placed DER at terminal 128 results the minimum ASIFI value with 95% confidence.

4.2.1.5.2. Analysis of ASIDI

ASIDI, (Average System Interruption Duration Index), indicates the total duration of interruption for the average customer during the period specified. Figure 4.22 shows the variation of ASIDI. It can be seen that ASIDI is minimized when DER is placed at terminal 128. Following hypothesis were constructed to analyze the significant.

H_0 = There is no difference in mean ASIDI when DERs are placed in selected terminals

H_1 = There is a difference in mean ASIDI when DERs are placed in selected terminals

Statistical software R, was used to do the analysis. The result below shows the output of the ANOVA test

```
           Df  Sum Sq  Mean Sq  F value  Pr(>F)
Exper       9   0.05   0.005    1.737  0.092 .
Term       10  91.70   9.170 3116.302 <2e-16 ***
Residuals  90   0.26   0.003
---
Signif. codes: 0   ***   0.001   **   0.01   *   0.05   .   0.1       1
```

The results shows that p-value for the variable Term (Terminal) is less than 0.05, which is the selected alpha level for 95% confidence interval. So we can reject the null hypothesis and we are 95% confidence that the the ASIDI will have different values depending on the selected location.

Dunnett multiple comparison was done to compare the ASIDI of other terminals with the selected terminal (Terminal 128).

```
         Simultaneous Tests for General Linear Hypotheses

Multiple Comparisons of Means: Dunnett Contrasts

Fit: aov(formula = ASIDI ~ Exper + Term, data = ASIDI_data)

Linear Hypotheses:

              Estimate Std. Error t value Pr(>|t|)

 4 - 128 == 0  0.32394   0.02426   13.353 < 1e-07 ***

 22 - 128 == 0 1.24372   0.02426   51.267 < 1e-07 ***

 32 - 128 == 0 2.44448   0.02426  100.763 < 1e-07 ***

 44 - 128 == 0 2.19196   0.02426   90.354 < 1e-07 ***

 55 - 128 == 0 0.21271   0.02426    8.768 < 1e-07 ***

 74 - 128 == 0 1.39015   0.02426   57.303 < 1e-07 ***

 79 - 128 == 0 0.14731   0.02426    6.072 1.93e-07 ***

100 - 128 == 0 2.67438   0.02426  110.240 < 1e-07 ***

119 - 128 == 0 1.45048   0.02426   59.790 < 1e-07 ***

156 - 128 == 0 1.49155   0.02426   61.483 < 1e-07 ***

---

Signif. codes: 0   ***   0.001   **   0.01   *   0.05   .   0.1       1
```

Dunnett multiple comparison compares ASIDI value when DER is at different terminals to ASIDI when DER is at 128. The results shows all the p-values are less than 0.05 which is our confidence level. This indicates that the ASIDI has significant different when placed in other terminals than terminal 128. The positive p-values at each comparison indicates that the minimum ASIDI value is produced when the DER is placed at terminal 128.

With these two tests we can conclude that when placed DER at terminal 128 results the minimum ASIDI value with 95% confidence.

4.2.1.5.3. Analysis of AENS

AENS, (Average Energy Not Supplied), indicates the average amount of energy not supplied, for all customers. Figure 4.22 shows the variation of AENS. It can be seen that AENS is minimized when DER is placed at terminal 128. Following hypothesis were constructed to analyze the significant.

H_0 = There is no difference in mean AENS when DERs are placed in selected terminals

H_1 = There is a difference in mean AENS when DERs are placed in selected terminals

Statistical software R, was used to do the analysis. The result below shows the output of the ANOVA test

```
          Df   Sum Sq  Mean Sq F value Pr(>F)
Exper      9 0.000121 0.0000134 20.88 <2e-16 ***
Term      10 0.017920 0.0017920 2786.14 <2e-16 ***
Residuals 90 0.000058 0.0000006
---
Signif. codes: 0   ***   0.001   **   0.01   *   0.05   .   0.1       1
```

The results shows that p-value for the variable Term (Terminal) is less than 0.05, which is the selected alpha level for 95% confidence interval. So we can reject the null hypothesis and we are 95% confidence that the the AENS will have different values depending on the selected location.

Dunnett multiple comparison was done to compare the AENS of other terminals with the selected terminal (Terminal 128).

```
         Simultaneous Tests for General Linear Hypotheses

Multiple Comparisons of Means: Dunnett Contrasts

Fit: aov(formula = AENS ~ Exper + Term, data = AENS_data)

Linear Hypotheses:

                Estimate Std. Error t value Pr(>|t|)

  4 - 128 == 0 0.0045317 0.0003587 12.635  <1e-05 ***

 22 - 128 == 0 0.0173912 0.0003587 48.489  <1e-05 ***

 32 - 128 == 0 0.0341774 0.0003587 95.292  <1e-05 ***

 44 - 128 == 0 0.0306482 0.0003587 85.452  <1e-05 ***

 55 - 128 == 0 0.0029729 0.0003587 8.289   <1e-05 ***

 74 - 128 == 0 0.0194297 0.0003587 54.173  <1e-05 ***

 79 - 128 == 0 0.0020607 0.0003587 5.746   <1e-05 ***

100 - 128 == 0 0.0373801 0.0003587 104.221 <1e-05 ***

119 - 128 == 0 0.0202732 0.0003587 56.525 <1e-05 ***

156 - 128 == 0 0.0208510 0.0003587 58.136 <1e-05 ***

---

Signif. codes: 0   ***   0.001   **   0.01   *   0.05   .   0.1        1
```

Dunnett multiple comparison compares AENS value when DER is at different terminals to AENS when DER is at 128. The results shows all the p-values are less than 0.05 which is our confidence level. This indicates that the AENS has significant different when placed in other terminals than terminal 128. The positive p-values at each comparison indicates that the minimum AENS value is produced when the DER is placed at terminal 128.

With these two tests we can conclude that when placed DER at terminal 128 results the minimum AENS value with 95% confidence.

4.2.1.6. Sensitivity analysis

How selected location will vary with the variation in load and the environmental condition was analyzed. The load can be vary as time progress. People buy new appliances and change their behavior to increase comfort. This increases the demand and can even change the its pattern. To analyze the sensitivity of the selected location, location selection with the increased demand was analyzed. The demand was increased by a percentage from the calculated demand and the location selected was studied. Table 4.10 shows the location selected with the increasing demand.

Table 4.10
Sensitivity analysis for the increase in demand

Increment in demand	Location	Selected location
5 %	-51.311, -20.432	Terminal 128
10 %	-51.311, -20.432	Terminal 128
15 %	-51.311, -20.432	Terminal 128
20 %	-51.311, -20.432	Terminal 128
25 %	-51.311, -20.432	Terminal 128

According to Butt (2011) the maximum variation of the load in central west Brazil is 20 %. From the table 4.10 we can see that the system gives the same location as the optimal location even if the load increase by 25%.

The selected location is also sensitive to the changes in the weather condition. The simulation rejects the wind generation as there is no sufficient wind speed available. The tool considered PV as the DER type to find the best capacity and location. Sensitivity analysis is done changing the available solar radiation to analyze the effect of that for on selected location. The analysis were done in grid connected mode to eliminate the inadequate of energy. Table 4.11 shows the selected location and the decrease in solar radiation.

Table 4.11
Sensitivity analysis for the decreasing solar radiation

Decrease in solar radiation	Location	Selected location
10 %	-51.311, -20.432	Terminal 128
20 %	-51.311, -20.432	Terminal 128
30 %	-51.299, -20.4412	Terminal 10
40 %	-	-

According to the data provided by the meteblue the daily average solar radiation is 724.76 W/m^2 (*meteoblue*, n.d.). The optimal location change when the solar radiation is reduced by 30%. Beyond this point the program eliminate the choice of solar PV due to lack of energy available. The distance between original location and the deviated location at 30 % less solar is 1.6 k.m.

Figure 4.24. Distance between selected optimal location and the location selected at 30% less solar radiation

4.3 Summary

This chapter provided the results obtained from the simulations. The first part of the chapter presented the results obtained from the MAS simulation to find the optimal location of the DER. Three methods were used to generate the load profiles during these simulations: random, survey based and behavior based. The second part of the chapter presented the results obtained from the behavioral model and compared those results with the actual data collected in from the lots. The final part of the chapter provided the results verifying the DER location selection improves the reliability of the system.According to section 4.2.1.5.1, 4.2.1.5.2 and 4.2.1.5.3 It can be seen that when DER is placed at terminal 128 minimize ASIFI, ASIDI and AENS respectively which maximize the reliability of the network. With all the results and analysis presented in this chapter we can conclude that the tool finds the optimal location, size and the type for DER to increase the reliability of the given network.

CHAPTER 5. CONCLUSION AND FUTURE IMPROVEMENTS

The thesis focused on evaluating the use of Multi Agent system for Distributed Energy Resource planning. The main objective of the MAS was to find the best location and determine the capacity for a DER to improve the reliability of the network. MAS also find the suitable type of the energy resources for a given location. This thesis was focused solely on solar PV and wind energy. Once the initial user input such as maximum allowable area for PV panels, maximum allowable hub hight, number of locations to be considered and number of capacities to be considered are provided through graphical user interface the tool runs without any user interaction to find the best location, capacity and type of the PV for a given distribution network.

MAS was developed utilizing GIS. GIS facilitates the integration of geographic data to the MAS. MAS obtains weather data, elevation data, as well as geographical locations of customers and other components in the network from GIS.

Coordinator agent in MAS provides time sync for the other agents. Coordinator agent is responsible for extracting data from the network modeled in the power system simulator. It will extract data from the power flow analysis and the reliability analysis in each time tic.

Building agents update their demand based on the consumer behavior. The behavior of the consumers in a building is determined by the appliances used and the weather data fetched from the weather agents. The building agents update the demand in the power system simulator. Building agents also calculate DERRI based on the the results from power flow analysis and reliability analysis.

The demand agents each represent the set of building agents and calculate gDERRI based on the DERRI of its child building agents. Demand agents also update its demand from the demands of the building agents associated with them.

DER agent in the MAS will travel around the world to find its best fit. DER agent in its travel communicate with the weather agents to collect weather data such as temperature, solar radiation, wind speed etc. This data helps the DER agent to determine the type of energy resource most suitable for a given location. The DER agent tries sets of capacities for each location. The DER agent bids for each capacity and the location during its travel. The bids are received by the grant agent. For each bid, grant agent creates the corresponding DER in the grid model in the PowerFactory and run the reliability and power flow analysis. The grant agent awards the DER agent based on the results obtained from the analysis and the objective function of the grant agent. DER agent generates the probability matrix based on the rewards obtained for each of the location and the capacity. The probability matrix defines how suitable a set of locations and the capacity, to improve the reliability of the power system with the DER placed at that location with the corresponding capacity. If minimizing the capacity is not an objective, the maximum probability in the probability matrix gives the optimal location. If minimizing the capacity is a part of the objective function the minimum probability value greater than the threshold gives the optimal location,capacity set for the DER.

The proposed human behavior model to predict the demand data. The correlation of the simulated hourly demand data to the actual demand is between 65% to 77% which is within one standard deviation. The statistical analysis presented in 4.2.1.5 shows that the selected location is statistically significant with 95% confidence interval.

5.1 Recommendation for future improvements

The DER planning tool used a commercial power system simulator to facilitate the modeling of the grid. The simulator provides the results of power flow and reliability analysis back to the MAS for the decision making. Relying on a commercial power system simulator is one of the limitations in the DER planing tool. Integration with a open source power system simulator or incorporating an own power system simulator can be considered in future work to improve the freedom of the tool.

It was noted that the tool consumes a large amount of the computer memory. The tool was run in a Intel(R) Core(TM) i3-2350M CPU @ 2.30 GHz processor in Windows environment with 6 GB memory. The average memory usage was 2.7 GB and the average CPU usage was 60%. The code has to be optimized and resource management techniques need to be adopted to improve the processing speed.

The customer behavior model governs the load variation of the network. The results show that the correlation between predicted hourly energy consumption and the actual hourly energy consumption is between 65% to 80%. The correlation can be improved by using one of the advanced modeling techniques such as fuzzy rule base, AI and neural network. The tool can be improved in the future to analyze the effect of feedback on the customer behavior. Before placing the DER, feedback techniques can be used to change the customer behavior pattern to reduce the energy consumption. After reductions of the energy consumption, DER allocation algorithm can be used to find the DER placement options. This approach can help to reduce the size of the DER units and associated costs.

APPENDICES

CHAPTER A. SOLAR PV PLANNING

Figure A.1 shows a typical connectivity of a PV system.

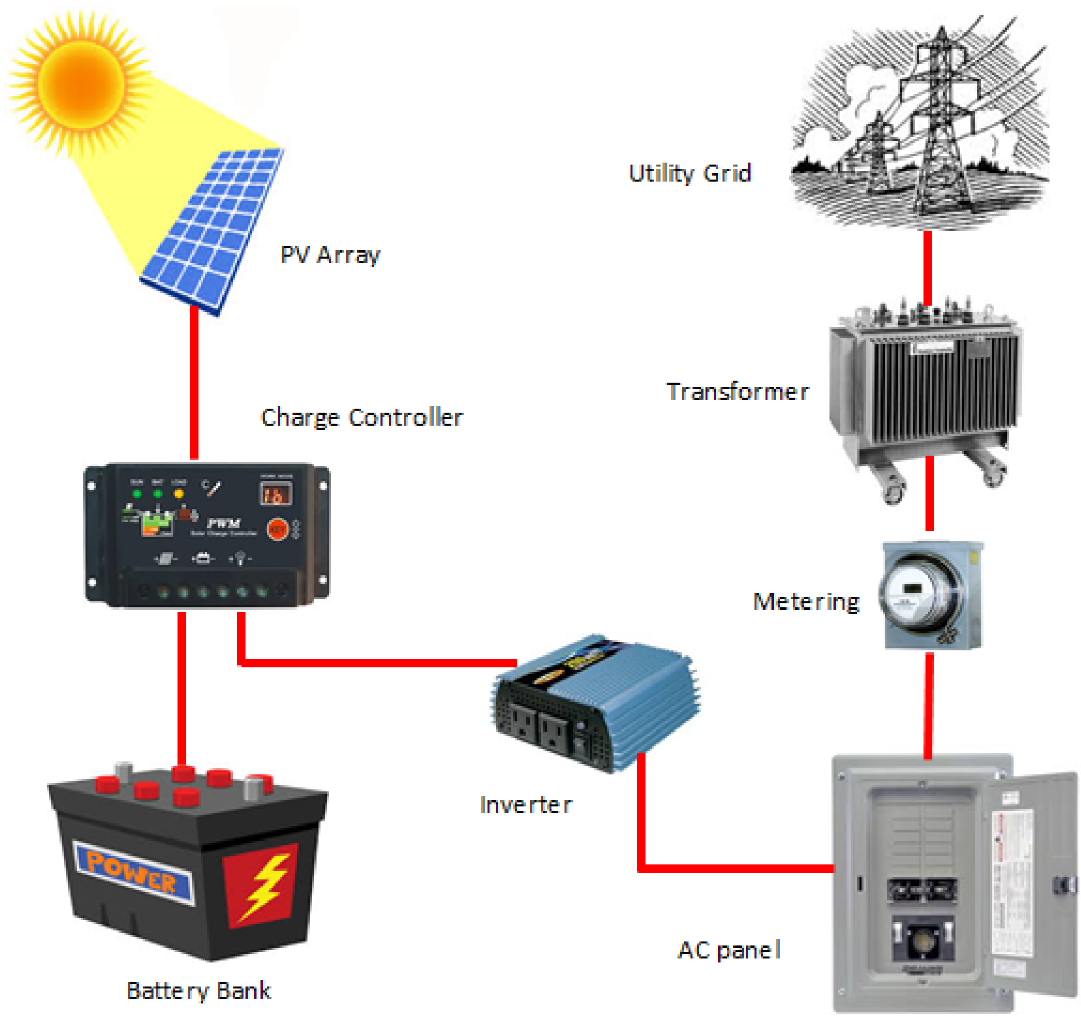


Figure A.1. Solar PV connectivity to utility grid and a battery bank

.

A PV system consists of:

- **PV array**

  Consists of several PV panels connected in series and parallel depending on the power and voltage requirement

- **Charge controller**

  Batteries will become damaged if they overcharge or if their voltage is pushed too high. This requires a controller between the PV array and the battery. Charge controllers will efficiently charge the batteries by controlling the charging voltage and the current.

- **Battery bank**

  Consists of series and parallel connected batteries to achieve desired capacity and voltage. Utilization of the batteries are optional depending on the system behavior. If the system is designed for use only during sun hours, there is no need for a battery bank. Battery banks are expensive and the technology is still under development.

- **Inverter**

  Used to convert DC output of the PV array to AC output which can be used by AC appliances and is suitable to connect to the utility grid.

- **AC panel**

  Consists of protection devices.

- **Utility metering/ net metering**

  Used to monitor power output of the solar system. In residential PV system, net metering is used to measure the power difference between consumption and the production from the PV system to the utility grid.

- **Step up transformer**

  Used in the system to convert the voltage level to match that of the utility grid.

Sizing the PV arrays, selecting proper inverter, selecting charge controller and other design considerations of a solar PV system will all be discussed in following sections.

A.1 Solar resources

Solar PV and solar thermal are the main form of energies from the sun that can be used to generate electricity. This paper focuses on solar PV for electricity generation. Accurate solar resource data is essential for the development of PV projects. Solar and meteorological data for the United States can be accessed from the NREL national solar radiation database (NREL, 2015). Clear guidance to use the data is given in the National Solar Radiation Database 1991-2010 Update: User's Manual (Wilcox, 2012). International solar radiation and meteorological data can be accessed from the meteoblue website (*meteoblue*, n.d.). Meteoblue provides access to its data online via standard API, special API or using JSON feed (meteoblue, n.d.). The data can also be requested in spreadsheet format. This research uses meteoblue data in spreadsheet format for past solar radiation, wind speed and other meteorological data. Meteoblue standard APIs are used to fetch current and future data.

Solar resource data is in two forms. One is derived from the satellite data and the other is based on ground measurements. The accuracy of each depends on the location (International Finance Corporation, 2012). Ground measurement data can be used to verify and fill the gaps in both satellite data and meteorological station data (International Finance Corporation, 2012). According to International Finance

Corporation (2012) Guide for Utility Scale Solar Power Plants, solar resources are inherently intermittent and an understanding of inter-annual variability is important.To get the variation to a good degree of confidence at least 10 years of data is required.

A.2 Solar PV project development

According to International Finance Corporation (2012) Guide for Utility Scale Solar Power Plants, solar PV projects can be divided in many phases:

- Phase 1 : Conceptual
- Phase 2 : Pre-feasibility study
- Phase 3 : Feasibility study
- Phase 4 : Design and development

A typical scope of the feasibility study includes (International Finance Corporation, 2012):

- Produce detailed site plan
- Calculate solar resources and other environmental conditions
- Outline the areas suitable for the solar PV development
- Assess technology options
- Outline system design
- Predict energy yields
- Asses stability

A.2.1 Site selection

This research focuses on using a given site for adding renewable energy resources. The site selection process has restrictions. Rather than selecting a best site considering solar resources, local climate, available area, land used, topography and other factors, the best locations within a given site have to be found by optimizing these parameters.

A.2.2 Solar PV system sizing

A.2.2.1. Determining power demand

To determine the power demand on the solar PV, one must first calculate the total kWh demand per day by all the loads connected to the PV system. Next, percentage demand that has to be covered by the solar PV system must be considered. Then, by considering the energy losses in the system the kWh generation needed per day by the Pv system can be calculated as:

$$kWh_{PV} = Dem_{total} \times \Delta_{dem} \times 1.3 \tag{A.1}$$

- kWh_{PV} is the generation needed by the PV system
- Dem_{total} is the total demand by connected loads
- Δ_{dem} is the percentage demand needed to be covered by the PV system $0 < \Delta_{dem} \leq 1$
- Constant 1.3 is to compensate for the energy losses. I.e. 30% more energy is produced than needed to compensate for the losses in the system.

A.2.2.2. Determining PV array size

The amount of energy produce by a solar panel depends on its technology and the size. The size of the solar PV system is determined by the demand and the available solar insolation.

- **Calculate average solar insolation**

  Annual solar insolation is calculated depending on the usage of the solar array. Since the solar insolation changes considerably based on the season, solar array can be used exclusively in summer or throughout the year and the average solar insolation is calculated accordingly.

  In this research it is assumed that the PV system is used throughout the year and year average of solar radiation is taken as the average solar radiation.

- **Calculate AH demand**

  To calculate the AH demand, the voltage rating of the solar array needs to be determined. 12 V, 24 V and 48 V are the typical system voltages. A single solar module gives a 12 V output. To get 24 V and 48 V, 2 and 4 solar modules need to be connected in series. The AH rate can be increased by connecting solar modules in parallel.

  In order to calculate AH demand, the average daily demand needs to be calculated. Since the demand varies depending the weather conditions and the season of the year, it is always recommended to get daily averages from the total yearly demand. Several years can be considered to increase the accuracy of the result.

  Once the average daily demand is calculated in WH, we divide that by the solar system output voltage to can calculate the AH demand per day.

- **Calculating PV array size**

The total current required by the loads can be calculated by dividing the AH demand per day by the total sun-hours per day. Sun-hours per day is a term used to express the solar insolation in kilowatt-hours per square meter per day in a given location. The values can be found using sun-hour (solar insolation) maps or by using meteorological or satellite data of solar insolation.

Once the total current required by the loads is calculated, dividing that by the rated current of the PV module selected will provide the number of modules that needs to be connected in parallel.

Once found the number of PV modules in series, which determined by the voltage and the number of PV modules in parallel, which determined by the AH demand or the total current demand, the total size of the PV array can be calculated using the equation

$$N_{PV,total} = N_{PV,series} \times N_{PV,parallel} \tag{A.2}$$

The power output of the PV array can be calculated using

$$P_{PV} = N_{PV,total} \times P_{nominal} \tag{A.3}$$

Where;

- P_{PV} is the total power output of the PV array
- $N_{PV,total}$ is the total number of PV modules in the array
- $P_{nominal}$ is the nominal power of a single PV module

A.2.3 PV plant design

Once the size of solar array is established the PV plant needs to be designed. The design of a PV plant focuses on achieving the lowest possible levelized cost of electricity (International Finance Corporation, 2012).

Selecting the correct battery storage and inverter for the solar system is important for the reliability of the system. The inverter selection has to sustain the PV sizing as well as meet government regulations on the grid connection. Details on selecting battery systems and inverters for PV arrays will be discussed in the next sub sections.

In designing the plant layout, the following factors need to be taken into consideration (International Finance Corporation, 2012):

- Reduce inner row shading by selecting proper raw spacing
- Choosing the layout to minimize the cable run and to minimize the associate power loss
- Choose the tilt angle that optimizes the annual energy yield
- Allow sufficient space between modules for maintenance purposes

According to the International Finance Corporation (2012) the electrical design of a PV project can be divided as DC system design and AC system design.

DC system consists of (International Finance Corporation, 2012) PV array, Inverter, Battery (if any), DC cabling, DC connectors, Junction boxes, Disconnect switches, Protection devices, and Earthing.

AC system consists of (International Finance Corporation, 2012), AC cabling, Switchgear, Transformers, Substation (for large scale projects), Earthing and surge protection

To build a reliable PV array all these systems need to be designed properly.

A.2.3.1. Charge controller selection

The first thing is to calculate is the amperage of the charge controller. The amperage of the charge controller is given by:

$$\text{Amperage of the charge controller} = \frac{\text{Wattage of the solar panel}}{\text{Battery bank voltage}} \tag{A.4}$$

Maximum Power Point Tracking (MPPT) charge controllers have more advantages than Pulse With Modulation (PWM) charge controllers. MPPT charge controllers will produce 30% more power output with extra cost. If cost is a limiting factor, a PWM charge controller can be used to fulfill the requirement.

A charge controller should be sized to pass all the arrays current to the battery. Oversizing the controller slightly can be beneficial since the controller will not have to work at the upper limits of its capacities all the time and can harvest any unexpected wattage that could come from extra irradiance or environmental conditions (Home power, 2010)

A.2.3.2. Battery bank selection

The sizing of the battery bank depends on the expected functionality of the bank. In a grid connected PV system the battery bank needs to be sized to meet the demand at the grid down time. In an isolated system the battery needs to be sized not only to meet the down time of the PV system but also the night time demand. Lowering the demand via energy management techniques comes in handy for this type of system to reduce extra cost on the battery bank.

In order to determine battery bank size, the first thing to calculate is the number of days that battery bank needs to supply demand without external charging. This can be calculated using historical data of grid outage time. Batteries have limited life times that are determined by the number of discharge cycles. Some deep cycle batteries can be discharged 80% for about 2000 cycles. These batteries can last longer if discharged to lower percentages. If discharged only 50%, the battery can last for about 4000 cycles. Typically for grid connected PVs, battery based backup systems may undergo 10 cycles per year (or even less) and sizing for 80% discharge rate is appropriate.

Once the desired days of autonomy, possible battery discharge levels and the energy requirements are calculated, the battery bank can be sized as follows.

Considering 85% efficient inverter:

$$\text{DC Wh per day requirement} = \frac{\text{Total Wh per day for backed up loads}}{0.85} \tag{A.5}$$

$$\text{DC Ah per day requirement} = \frac{\text{DC Wh per day requirement}}{\text{Nominal battery Voltage}} \tag{A.6}$$

Considering maximum Day of Discharge (DOD) of 80%, leaving the battery at 20% charge after a day of discharge.

$$\text{Adjusted DC Ah total} = \frac{\text{DC Ah per day requirement}}{0.8} \times \text{Days of autonomy} \tag{A.7}$$

To determine the number of parallel batteries in the string, considering 20 h discharge rate and dividing the adjusted DC Ah total by the capacity rating of the chosen battery as:

$$\text{Number of parallel batteries} = \frac{\text{Adjusted DC Ah total}}{\text{Battery capacity rating}} \tag{A.8}$$

The number of cells in series is determined by the nominal battery bank voltage.

A.2.3.3. Inverter selection

According to Home power (2010) the inverter in a grid tied system with battery banks must be sized to do two things. First is to power all the loads supplied by the PV system. Second is to simultaneously pass the energy from the PV system to the grid.

To calculate the inverter power rating the total amount of demand supplied by the PV system must be calculated. The inverter should be able to handle any surge loads in the network and sized to handle the the maximum combined surge loads. Inverters are capable of handling twice their rated surge capacity for few seconds. Total power output and the surge capacity can be increased by stacking the outputs of multiple inverters (Home power, 2010).

The rated power of the inverter needs to be determined according to the power generated by the PV array. The inverter should be able to handle the rated capacity of the PV array. Typical production of a solar panel is much less than its rated value, there is a probability that the solar array will produce its rated power and the inverter should be able to handle that.

The inverter should be selected to handle whichever the larger of these two factors: PV array output or maximum combined demand. Finally, inverter nominal voltage and the frequency should match that of the loads.

A.2.4 Other components

- **Bypass breaker** is used to isolate all loads from the PV system and to power them directly from the grid.
- **Battery meter** reports the status of the battery system. These will typically display the voltage, amperage and battery state of charge.
- **Net meter** is used to monitor the power output of the PV system. Also can be used to measure the power demand from the grid when the loads are not supported by the PV or when PV doesn't have enough energy to supply the loads.

CHAPTER B. WIND PLANNING

B.1 Wind resources and speeds

Quantifying the wind speed at the location of interest is the cornerstone of a wind project. The power of the wind varies greatly from one location to the other. Some of the best resources are found on agricultural lands with large open areas. There are two initial steps to be followed (WINDUSTRY, 2015):

1. Determine the size of the wind plant
    - Small (< 10 kW)
    - Medium (10 kW $\sim$ 250 kW)
    - Large (> 250 kW)
2. Determine how much wind is across the site

If confident with the wind profile, then its time to decide what type of a turbine you want to install, your lifestyle and profit goals may tell you whether a wind project is worth your time (WINDUSTRY, 2015).

B.1.1 Wind Speed

Wind speed is the most important factor to consider in planning a wind farm. Wind speed is susceptible to variation depending on the year, season, day and the height above the ground (WINDUSTRY, 2015). Wind speed data can be found online as wind maps. Wind data archived for longer periods of time (3 to 5 years) is available online. These data are a good starting point to determine the fluctuation of wind and the annual average of the site. Since the resolution of these data for some parts of the world is limited it is always advisable to gather metrological data at the site to finalize the decision. The relation between power produced and the wind speed is given by the equation B.1.

$$P = (\frac{1}{2}\rho v^3 \pi r^2)\eta \tag{B.1}$$

Where:

η is the efficiency efficiency of the wind turbine. ρ is the air density which varies depending on the elevation and the air temperature. Air density decreases as elevation increases, and decreases when temperature increases.

r is the radius of the circle formed by turbine's blades. This circle is sometimes called the turbine's rotor disk. r is the length of the blades.

v is the wind speed which varies depending on the elevation. There are number of laws that can be used to calculate wind at a given height (Chen, Cheng, & Hoff, n.d.):

- **Logarithmic law** is one of them:

  Logarithmic law is expressed as

$$v = \frac{1}{k} v_* ln \frac{Z}{Z_0} \tag{B.2}$$

  Where :

  v : Wind speed at height Z in m/s

  k : von Karman constant (≈ 0.4)

  Z_0 : Ground roughness

v_* : shear velocity defined as

$$v_* = \sqrt{\frac{\tau_0}{\rho}} \tag{B.3}$$

where τ_0 is the stress of wind at ground level and ρ is the air density

- **Power law 1** gives the relationship of the wind speed and the elevation as :

$$v_2 = v_1 \left[\frac{Z_2}{Z_!}\right]^{b_2} \tag{B.4}$$

Where v_1 and Z_1 are the wind speeds and the elevations at a lower level. v_2 and Z_2 are the wind speed and the elevation at a higher level. b_2 (also called α) is the wind share component

- **Power law 2** gives the relationship of the wind speed and the elevation as :

$$v = b_1 Z^{b_2} + b_3 \tag{B.5}$$

The exponential function based laws to determine wind speed are:

- **Exponential law 1**

$$v = b_1 e^{-b_2 Z} \tag{B.6}$$

- **Exponential law 2**

$$v = b_1 e^{-b_2 Z} + b_3 \tag{B.7}$$

The same set of equations can be used to find the wind speed at a given height compared to a known speed at a reference height. Power law 1 and the logarithmic law are both widely used for this purpose.

B.2 Factors to consider when deploying a wind project

The first factor to be considered is the wind speed. As discussed in chapter B.1, wind speed data can be found using wind resource maps. Wind resource maps will show the areas where good wind resource can be expected (Oklahoma Cooperative Extension Service, n.d.).

The availability of transmission lines is important to reduce the capital cost. Building new transmission lines will increase the capital cost of the project and hence the payback time. It is always preferable to have existing transmission lines closer to the wind stations (Oklahoma Cooperative Extension Service, n.d.).

The noise and the shadow flicker should be taken in to account to reduce the discomfort to the neighbors. There are proper guidelines to reduce the burden on the neighbors. As a rule of thumb, the site should be 650 meters away from the inhabited areas (Local United, 2011). There can be exceptions for medium scale turbines and when higher noises (noises from highways) already exists (Local United, 2011). GIS tools can be used to find habitat areas and plan the turbine placements based on the guidelines.

Designated areas like national parks, areas with outstanding national beauties, and sites with scientific interests need to be eliminated. Easy access to the site is important in installation phase as well as for maintenance access. 2MW wind turbines have blades that are approximately 45 m long that can't be bend and tower sections that are considerably wide. Transporting these requires easy access with wide roads without deep bends (Local United, 2011).

According to Local United (2011) ecological constraints are a major limitation on where to put a wind turbines. Bird migration paths should be avoided at all cost. The locations with high bird activities are not suitable for a wind turbine and could cause problems. In some cases, impact on wide life can be mitigated with detailed planning procedure. Detail studies of the behavior of wild life is needed for this type of situations.

Placement of wind turbines could also cause interference with radio signals for mobile tours, TV stations and radio stations. Planning of wind turbine placement needs to investigate and address these types of issues as well.

When all these factors can be addressed and the location is identified to install the wind turbines, detailed financial analysis needs to be carried out to investigate the fiscal feasibility. According to Local United (2011), the money needed falls in to two categories:

Risk Money (Development Cost)	**Capital (Construction cost)**
Initial assessment	Turbine, transformers etc.
Feasibility and technical work	Groundworks
Planning and permitting	Grid connection
Legals	Installation
Finding the fund	

CHAPTER C. BEHAVIOR MODEL

The behavior model is used to model the behavior of households in operating different appliances. The objective of this model is to identify the different appliances used in a given time of the day and hence calculate the total demand at that time. Figure C.1 shows the high level view of the model.

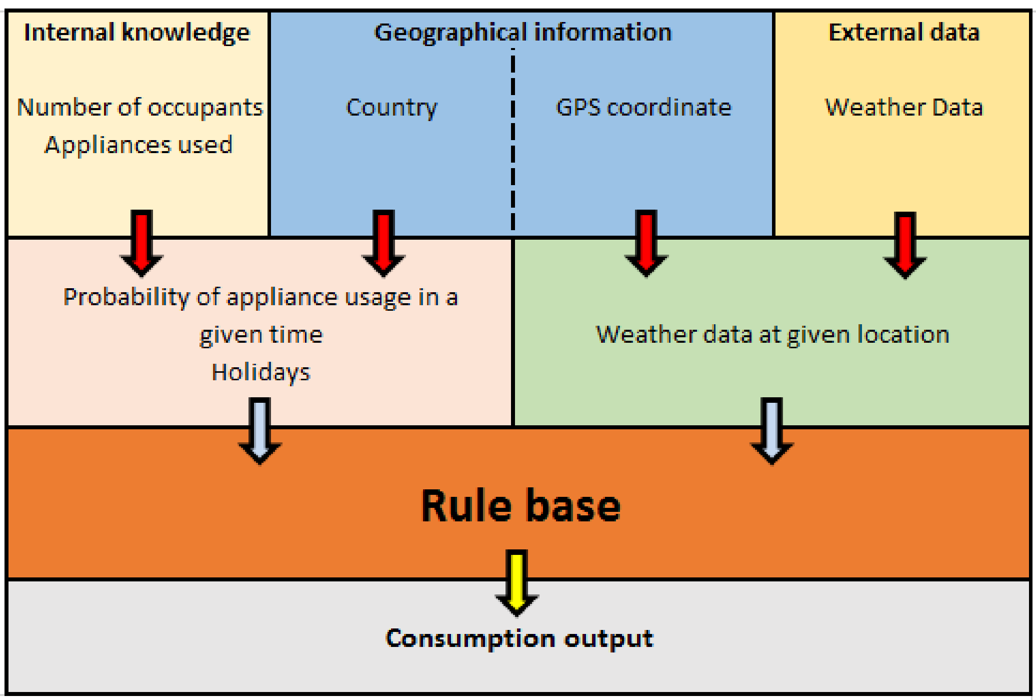


Figure C.1. Human behavior model to simulate the hourly power consumption

Each building agent has its internal knowledge which consists of the number of occupants and the different appliances used in the household. Each building agent also has a GPS coordinate associated with it which determines its exact location and the country it belongs to. Building agents fetch information such as weather data and GIS data from external agents. This is indicated as external data in the figure C.1.

The probability of appliance usage in a given time varies depending on the geographical location. This data can be found in different literatures or can be collected via a survey. The energy consumed by different appliances can also be found in the literature. The author has also developed a data collection system to collect appliance energy consumption patterns (Navaratne, Kulatunga, Redmond, & Sampaio, 2015).

The data can be uploaded to the model as a text file. The energy consumption pattern also varies during the holidays. The list of holidays for the country can also be uploaded in to the model.

Building agents communicate with external agents to extract the external data needed including weather data such as temperature, humidity and precipitation in its location. Information extracted from the knowledge base and external agents is then fetch to the rule-base. Rule-base is a structured rule-base which consists of multiple conditional statements. The rule base can be improved by including a fuzzy logic rule base system. But in this research rule-base is limited to a conditional statements.

The output of the rule-base system is the hourly electrical energy consumption of each household.

The logic in the rule-based system can be expressed mathematically as below.

If we have appliance vector A s.t.

$$A = [a_1 \quad a_2 \quad ..... \quad a_N]$$

and

$$U = [u_1 \quad u_2 \quad ..... \quad u_L]$$

is the set of users and H is the appliance ownership matrix given by

$$H_{i,k} = \begin{cases} 1, & \text{if Appliance } a_i \text{ is owned by customer } u_k \\ 0, & \text{otherwise} \end{cases}$$

Let's consider the user u_k ;

Then the power demand/consumed by the u_k at a given time t_j is given by

$$P_{u_k}^{t_j} = \sum_{i=1}^{N} Pr_{a_i}^{t_j} W_{a_i}^{R} H_{i,k}$$

Where

$W_a^R = [W_{a_1}^R \quad W_{a_2}^R \quad .... \quad W_{a_N}^R]$ is the rated power of appliances and

$Pr_{a_i}^{t_j}$ is the probability of appliance a_i used at time t_j

The $Pr_{a_i}^{t_j}$ varies depending on the number of consumers in the household, the environment conditions such as temperature, humidity etc. and other external factors. The model updates the probability of appliances used based on these parameters.

For an example the pump operate to water the plant has the typical operational behavior shown in figure C.2. The figure C.3 shows the variation of the probability of operation with the amount of precipitation.

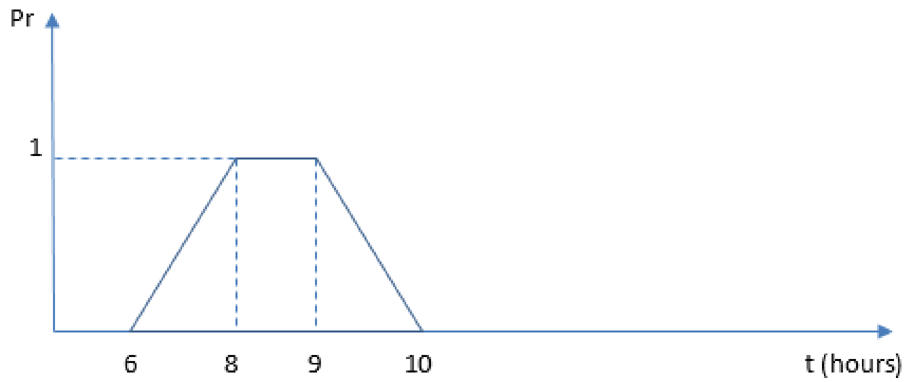


Figure C.2. Variation of the probability of operation of well pump to water the plants during the day]

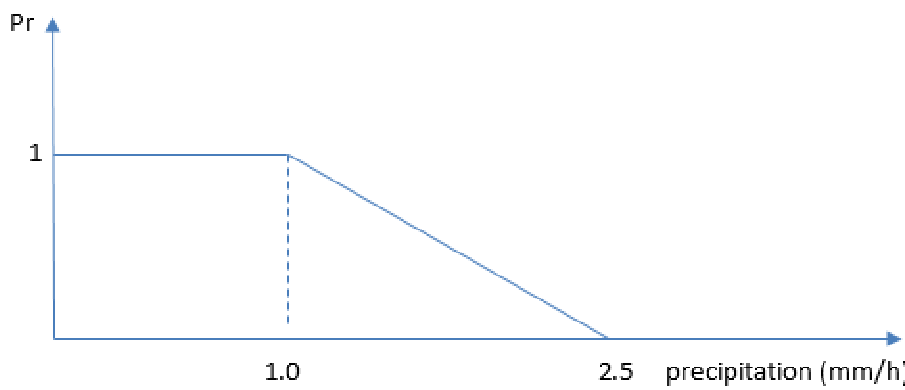


Figure C.3. Variation of the probability of operation of well pump to water the plants depending on the precipitation

According to the figure C.2, in a typical day the probability of using the pump between 8.00 am to 9.00 am is equal to 1. If the precipitation is greater than 1 mm/h this probability start decreasing. If the precipitation exceed 2.5 mm/h the watering is not required at all and the probability of operating the pump become zero.

Similar rule base system is applied to the other appliances based on their typical usage pattern.

CHAPTER D. POWER FLOW ANALYSIS RESULTS

This chapter presents the results of the power flow analysis for the original power system, without any DERs in the network. The analysis was done for the worst case scenario with all loads at their declared maximum capacity. Section D.1 presents the power flow results for each load and the line segments in the network.

The description of the columns are:

- **Name**: This is the name given to the component in the power system model (ex: Generator, load or the line segment)
- **Type**: Indicates the type of the component:
  - Loadlv : Low voltage load
  - Line : Transmission or distribution line
  - GenStat: Static generators
  - TR2: Two winding transformers
- **Loading**: The loading level of the component. Applicable only for certain types of components such as power lines, transformers, generators
- **Busbar**: Represents the nodes or the bus bars that the component is connected. single terminal components such as loads only have one Busbar attached to it. Two terminal components such as lines and transformers have two busbars attached to them.
- **Active Power [kW]**: Active power flow in to or out of the component

- **Reactive Power [Kvar]**:Reactive power flow in to or out of the component
- **Powerfactor**: Power factor associated with the component
- **Current [A]**: Current flow in to or out of the component in amperes
- **Current [p.u.]**: Current flow in to or out of the component in per units

Initial power flow analysis was performed to ensure the system functionality. Convergence of power flow indicate that the system has adequate generation compared to its load demand. During the runtime of the DER allocation tool Power flow analysis was performed after placing DER at each location to make sure it converge and hence the DER is capable of supplying the demand of the system when placed at that location.

D.1 Initial power flow analysis for the worst case scenario: loads and lines

Load Flow Calculation			Edge Elements
AC Load Flow, unbalanced, 3-phase (ABC)		Automatic Model Adaptation for Convergence	No
Automatic Tap Adjust of Transformers	No	Max. Acceptable Load Flow Error for	
Consider Reactive Power Limits	No	Nodes	1.00 kVA
		Model Equations	0.10 %

		DIgSILENT PowerFactory 15.1.7	Project:
			Date: 1/23/2016
Grid: IlhaGrid	System Stage: IlhaGrid	Study Case: Study Case	Annex: / 1

Name	Type	Loading [%]	Busbar	Active Power [kW]	Reactive Power [kvar]	Power.- factor [-]	Current [A]	Current [p.u.]
Static Generator	Genstat	0.00		0.000	0.000	1.00	0.000	0.000
Static Generator(1)	Genstat	0.00	Terminal(176)	0.000	0.000	1.00	0.000	0.000
101	Lodlv		Terminal(12)	6.568	4.926	0.80	35.915	1.743
103	Lodlv		Terminal(17)	6.728	5.046	0.80	36.822	1.744
103-105	Lodlv		Terminal(9)	3.256	2.442	0.80	17.840	1.746
105	Lodlv		Terminal(9)	5.896	4.422	0.80	32.304	1.746
107	Lodlv		Terminal(13)	6.880	5.160	0.80	37.717	1.747
109	Lodlv		Terminal(15)	6.752	5.064	0.80	37.032	1.748
111	Lodlv		Terminal(19)	6.856	5.142	0.80	37.673	1.751
115	Lodlv		Terminal(24)	6.832	5.124	0.80	37.552	1.752
116	Lodlv		Terminal(29)	6.800	5.100	0.80	37.383	1.752
117	Lodlv		Terminal(31)	6.696	5.022	0.80	36.827	1.753
118	Lodlv		Terminal(31)	7.040	5.280	0.80	38.719	1.753
119	Lodlv		Terminal(26)	5.896	4.422	0.80	33.479	1.810
120	Lodlv		Terminal(26)	6.056	4.542	0.80	34.388	1.810
121	Lodlv		Terminal(26)	5.896	4.422	0.80	33.479	1.810
122	Lodlv		Terminal(21)	5.768	4.326	0.80	31.708	1.752
123	Lodlv		Terminal(21)	5.896	4.422	0.80	32.411	1.752
124	Lodlv		Terminal(19)	6.880	5.160	0.80	37.805	1.751
125	Lodlv		Terminal(35)	4.456	3.342	0.80	24.473	1.750
126	Lodlv		Terminal(35)	6.056	4.542	0.80	33.261	1.750
127	Lodlv		Terminal(40)	5.048	3.786	0.80	28.601	1.806
128	Lodlv		Terminal(41)	7.256	5.442	0.80	39.895	1.752
129	Lodlv		Terminal(43)	6.000	4.500	0.80	32.988	1.752
130	Lodlv		Terminal(43)	6.056	4.542	0.80	33.296	1.752
131	Lodlv		Terminal(41)	5.976	4.482	0.80	32.857	1.752
132	Lodlv		Terminal(114)	6.575	4.932	0.80	37.821	1.835
133	Lodlv		Terminal(114)	5.822	4.367	0.80	33.490	1.835
134	Lodlv		Terminal(117)	6.936	5.202	0.80	38.476	1.768
135	Lodlv		Terminal(114)	7.040	5.280	0.80	40.492	1.835
136	Lodlv		Terminal(101)	6.112	4.584	0.80	33.892	1.767
137	Lodlv		Terminal(97)	6.936	5.202	0.80	38.410	1.765

Grid: IlhaGrid	System Stage: IlhaGrid	Study Case: Study Case	Annex: / 2

Name	Type	Loading [%]	Busbar	Active Power [kW]	Reactive Power [kvar]	Power.- factor [-]	Current [A]	Current [p.u.]
138	Lodlv		Terminal(50)	6.696	5.022	0.80	36.796	1.751
139	Lodlv		Terminal(40)	5.816	4.362	0.80	32.952	1.806
140	Lodlv		Terminal(40)	6.056	4.542	0.80	34.312	1.806
141	Lodlv		Terminal(36)	6.696	5.022	0.80	36.781	1.751
143	Lodlv		Terminal(13)	6.592	4.944	0.80	36.138	1.747
144	Lodlv		Terminal(95)	6.696	5.022	0.80	37.064	1.764
145	Lodlv		Terminal(9)	6.696	5.022	0.80	36.687	1.746
146	Lodlv		Terminal(90)	7.936	5.952	0.80	43.893	1.763
147	Lodlv		Terminal(17)	6.616	4.962	0.80	36.209	1.744
148	Lodlv		Terminal(75)	6.672	5.004	0.80	36.879	1.762
149	Lodlv		Terminal(12)	7.288	5.466	0.80	39.852	1.743
150	Lodlv		Terminal(72)	6.992	5.244	0.80	38.621	1.760
151	Lodlv		Terminal(6)	7.672	5.754	0.80	41.890	1.740
152	Lodlv		Terminal(70)	6.912	5.184	0.80	38.144	1.759
153	Lodlv		Terminal(5)	5.896	4.422	0.80	32.147	1.738
154	Lodlv		Terminal(64)	8.016	6.012	0.80	44.203	1.757
155	Lodlv		Terminal(52)	6.696	5.022	0.80	36.871	1.755
156	Lodlv		Terminal(58)	6.616	4.962	0.80	36.438	1.755
157	Lodlv		Terminal(47)	6.696	5.022	0.80	37.826	1.800
158	Lodlv		Terminal(80)	6.568	4.926	0.80	35.834	1.739
159	Lodlv		Terminal(82)	6.856	5.142	0.80	37.481	1.742
160	Lodlv		Terminal(85)	6.696	5.022	0.80	36.671	1.745
161	Lodlv		Terminal(87)	4.936	3.702	0.80	27.086	1.749
162	Lodlv		Terminal(56)	4.992	3.744	0.80	27.444	1.752
163	Lodlv		Terminal(61)	6.912	5.184	0.80	38.097	1.757
164	Lodlv		Terminal(61)	6.800	5.100	0.80	37.480	1.757
165	Lodlv		Terminal(67)	8.624	6.468	0.80	47.590	1.759
166	Lodlv		Terminal(127)	6.912	5.184	0.80	38.217	1.762
167	Lodlv		Terminal(120)	6.800	5.100	0.80	37.570	1.761
168	Lodlv		Terminal(123)	6.856	5.142	0.80	37.908	1.762
169	Lodlv		Terminal(92)	7.360	5.520	0.80	40.739	1.764
171	Lodlv		Terminal(92)	5.416	4.062	0.80	29.978	1.764
172	Lodlv		Terminal(121)	6.912	5.184	0.80	38.230	1.763
173	Lodlv		Terminal(99)	6.696	5.022	0.80	37.099	1.766
174	Lodlv		Terminal(121)	5.952	4.464	0.80	32.921	1.763
175	Lodlv		Terminal(101)	6.160	4.620	0.80	34.158	1.767
176	Lodlv		Terminal(104)	6.728	5.046	0.80	37.300	1.767
177	Lodlv		Terminal(106)	6.800	5.100	0.80	37.705	1.767
178	Lodlv		Terminal(109)	6.936	5.202	0.80	38.466	1.767
179	Lodlv		Terminal(111)	8.280	6.210	0.80	45.930	1.768
180	Lodlv		Terminal(116)	6.912	5.184	0.80	38.340	1.768
181	Lodlv		Terminal(130)	6.880	5.160	0.80	37.813	1.752
182	Lodlv		Terminal(136)	6.376	4.782	0.80	35.121	1.756
183	Lodlv		Terminal(136)	6.136	4.602	0.80	33.799	1.756
184	Lodlv		Terminal(160)	7.992	5.994	0.80	44.083	1.758

Grid: IlhaGrid System Stage: IlhaGrid | Study Case: Study Case | Annex: / 3

Name	Type	Loading [%]	Busbar	Active Power [kW]	Reactive Power [kvar]	Power.-factor [-]	Current [A]	Current [p.u.]
185	Lodlv		Terminal(161)	6.832	5.124	0.80	37.690	1.758
186	Lodlv		Terminal(163)	6.696	5.022	0.80	36.925	1.757
187	Lodlv		Terminal(165)	4.912	3.684	0.80	27.091	1.758
188	Lodlv		Terminal(166)	7.840	5.880	0.80	43.253	1.758
189A	Lodlv		Terminal(167)	8.760	6.570	0.80	48.363	1.760
189B	Lodlv		Terminal(167)	9.208	6.906	0.80	50.837	1.760
190	Lodlv		Terminal(168)	4.912	3.684	0.80	27.097	1.758
200	Lodlv		Terminal(151)	8.608	6.456	0.80	47.497	1.758
201	Lodlv		Terminal(151)	6.912	5.184	0.80	38.139	1.758
202	Lodlv		Terminal(160)	9.000	6.750	0.80	49.643	1.758
203	Lodlv		Terminal(161)	8.240	6.180	0.80	45.458	1.758
55	Lodlv		Terminal(152)	6.568	4.926	0.80	36.237	1.758
57	Lodlv		Terminal(152)	6.568	4.926	0.80	36.237	1.758
59	Lodlv		Terminal(149)	6.696	5.022	0.80	36.924	1.757
61	Lodlv		Terminal(146)	6.696	5.022	0.80	36.920	1.757
62	Lodlv		Terminal(143)	6.696	5.022	0.80	36.910	1.757
62 branch	Lodlv		Terminal(169)	0.000	0.000	1.00	0.000	0.000
62 branch(1)	Lodlv		Terminal(170)	0.000	0.000	1.00	0.000	0.000
63	Lodlv		Terminal(139)	7.304	5.478	0.80	40.194	1.754
67	Lodlv		Terminal(133)	6.856	5.142	0.80	37.702	1.753
83	Lodlv		Terminal(82)	9.320	6.990	0.80	50.952	1.742
87	Lodlv		Terminal(78)	8.840	6.630	0.80	48.148	1.736
89	Lodlv		Terminal(78)	6.080	4.560	0.80	33.115	1.736
91	Lodlv		Terminal(47)	6.696	5.022	0.80	37.826	1.800
93	Lodlv		Terminal(47)	7.756	5.337	0.82	42.547	1.800
95	Lodlv		Terminal(5)	6.592	4.944	0.80	35.942	1.738
97	Lodlv		Terminal(6)	5.768	4.326	0.80	31.494	1.740
99	Lodlv		Terminal(7)	6.880	5.160	0.80	37.582	1.741
Equivalent Load	Lodlv		Terminal(171)	0.000	0.000	1.00	0.000	0.000
Equivalent Load(1)	Lodlv		Terminal(172)	0.000	0.000	1.00	0.000	0.000
Low-Voltage Load	Lodlv			0.000	0.000	1.00	0.000	0.000
Low-Voltage Load(1)	Lodlv			0.000	0.000	1.00	0.000	0.000
Shunt/Filter(4)	Shnt		Single Busbar with ..	-0.000	-500.000	-0.00	20.918	1.000
External Grid	Xnet		Single Busbar with ..	704.720	77.914	0.99	29.664	0.000
Line	Lne	16.47	Terminal	-247.030	-199.989	-0.78	23.059	0.165
			Terminal(4)	247.207	200.042	0.78	23.059	0.165
Line(1)	Lne	16.02	Terminal	240.069	194.889	0.78	22.434	0.160
			Terminal(8)	-239.695	-194.779	-0.78	22.434	0.160
Line(1)_a	Lne	15.17	Terminal(8)	227.004	184.371	0.78	21.242	0.152
			Terminal(10)	-226.587	-184.248	-0.78	21.242	0.152
Line(1)_b	Lne	14.26	Terminal(10)	212.944	173.126	0.78	19.961	0.143
			Terminal(1)	-212.704	-173.055	-0.78	19.961	0.143
Line(10)	Lne	4.57	Terminal(2)	67.808	55.226	0.78	6.399	0.046
			Terminal(173)	-67.803	-55.225	-0.78	6.399	0.046
Line(10)_a	Lne	3.84	Terminal(39)	57.089	46.318	0.78	5.379	0.038

Grid: IlhaGrid System Stage: IlhaGrid | Study Case: Study Case | Annex: / 4

Name	Type	Loading [%]	Busbar	Active Power [kW]	Reactive Power [kvar]	Power.-factor [-]	Current [A]	Current [p.u.]
			Terminal(42)	-57.059	-46.309	-0.78	5.379	0.038
Line(10)_b	Lne	3.36	Terminal(42)	50.166	40.272	0.78	4.709	0.034
			Terminal(44)	-50.145	-40.266	-0.78	4.709	0.034
Line(10)_c	Lne	2.22	Terminal(44)	32.588	27.056	0.77	3.102	0.022
			Terminal(46)	-32.585	-27.055	-0.77	3.102	0.022
Line(10)_d	Lne	1.74	Terminal(46)	25.692	21.019	0.77	2.431	0.017
			Terminal(49)	-25.687	-21.017	-0.77	2.431	0.017
Line(10)_e	Lne	0.83	Terminal(49)	12.256	10.066	0.77	1.162	0.008
			Terminal(37)	-12.255	-10.066	-0.77	1.162	0.008
Line(11)	Lne	0.73	Terminal(39)	10.711	8.906	0.77	1.019	0.007
			Terminal(38)	-10.710	-8.906	-0.77	1.019	0.007
Line(12)_a	Lne	14.58	Terminal(55)	213.388	179.053	0.77	20.411	0.146
			Terminal(57)	-212.888	-178.905	-0.77	20.411	0.146
Line(12)_b	Lne	14.10	Terminal(57)	206.076	172.934	0.77	19.746	0.141
			Terminal(59)	-206.009	-172.914	-0.77	19.746	0.141
Line(12)_c	Lne	13.16	Terminal(59)	192.097	161.606	0.77	18.430	0.132
			Terminal(62)	-191.865	-161.538	-0.76	18.430	0.132
Line(12)_d	Lne	12.60	Terminal(62)	183.653	154.517	0.77	17.636	0.126
			Terminal(66)	-183.483	-154.467	-0.77	17.636	0.126
Line(12)_e	Lne	11.99	Terminal(66)	174.663	146.990	0.77	16.786	0.120
			Terminal(69)	-174.626	-146.979	-0.77	16.786	0.120
Line(12)_f	Lne	11.49	Terminal(69)	167.519	140.789	0.77	16.093	0.115
			Terminal(48)	-167.371	-140.746	-0.77	16.093	0.115
Line(13)	Lne	0.48	Terminal(46)	6.893	6.036	0.75	0.671	0.005
			Terminal(51)	-6.893	-6.036	-0.75	0.671	0.005
Line(14)	Lne	9.13	Terminal(48)	133.106	111.635	0.77	12.784	0.091
			Terminal(71)	-133.060	-111.622	-0.77	12.784	0.091
Line(14)_a	Lne	8.63	Terminal(71)	125.873	105.374	0.77	12.083	0.086
			Terminal(74)	-125.744	-105.335	-0.77	12.083	0.086
Line(14)_b	Lne	8.15	Terminal(74)	118.877	99.329	0.77	11.411	0.082
			Terminal(88)	-118.795	-99.305	-0.77	11.411	0.082
Line(14)_c	Lne	7.59	Terminal(88)	110.664	92.350	0.77	10.623	0.076
			Terminal(91)	-110.591	-92.329	-0.77	10.623	0.076
Line(14)_d	Lne	6.71	Terminal(91)	97.619	81.734	0.77	9.388	0.067
			Terminal(93)	-97.566	-81.718	-0.77	9.388	0.067
Line(14)_e	Lne	6.22	Terminal(93)	90.676	75.697	0.77	8.713	0.062
			Terminal(96)	-90.620	-75.681	-0.77	8.713	0.062
Line(14)_f	Lne	5.73	Terminal(96)	83.490	69.480	0.77	8.016	0.057
			Terminal(98)	-83.434	-69.463	-0.77	8.016	0.057
Line(14)_g	Lne	5.24	Terminal(98)	76.544	63.444	0.77	7.341	0.052
			Terminal(100)	-76.495	-63.429	-0.77	7.341	0.052
Line(14)_i	Lne	3.91	Terminal(102)	57.093	47.171	0.77	5.472	0.039
			Terminal(105)	-57.081	-47.168	-0.77	5.472	0.039
Line(14)_j	Lne	3.42	Terminal(105)	50.087	41.072	0.77	4.786	0.034
			Terminal(107)	-50.075	-41.068	-0.77	4.786	0.034

Grid: IlhaGrid	System Stage: IlhaGrid	Study Case: Study Case	Annex: / 5

Name	Type	Loading [%]	Busbar	Active Power [kW]	Reactive Power [kvar]	Power.-factor [-]	Current [A]	Current [p.u.]
Line(14)_l	Lne	2.33	Terminal(110)	34.464	27.660	0.78	3.266	0.023
			Terminal(112)	-34.464	-27.660	-0.78	3.266	0.023
Line(14)_m	Lne	1.00	Terminal(112)	14.236	12.377	0.75	1.394	0.010
			Terminal(115)	-14.235	-12.377	-0.75	1.394	0.010
Line(14)_n	Lne	0.50	Terminal(115)	7.130	6.198	0.75	0.698	0.005
			Terminal(54)	-7.129	-6.197	-0.75	0.698	0.005
Line(15)	Lne	0.47	Terminal(57)	6.812	5.971	0.75	0.665	0.005
			Terminal(60)	-6.812	-5.971	-0.75	0.665	0.005
Line(16)	Lne	0.94	Terminal(59)	13.912	11.308	0.78	1.316	0.009
			Terminal(63)	-13.911	-11.308	-0.78	1.316	0.009
Line(17)	Lne	0.57	Terminal(62)	8.212	7.021	0.76	0.794	0.006
			Terminal(65)	-8.212	-7.021	-0.76	0.794	0.006
Line(18)	Lne	0.61	Terminal(66)	8.820	7.477	0.76	0.850	0.006
			Terminal(68)	-8.820	-7.477	-0.76	0.850	0.006
Line(19)	Lne	0.50	Terminal(71)	7.187	6.248	0.75	0.701	0.005
			Terminal(73)	-7.187	-6.248	-0.75	0.701	0.005
Line(2)	Lne	13.77	Terminal(1)	205.624	166.869	0.78	19.278	0.138
			Terminal(14)	-205.461	-166.821	-0.78	19.278	0.138
Line(2)_a	Lne	12.83	Terminal(14)	191.403	155.389	0.78	17.958	0.128
			Terminal(16)	-191.172	-155.321	-0.78	17.958	0.128
Line(2)_b	Lne	11.92	Terminal(16)	177.627	144.276	0.78	16.683	0.119
			Terminal(18)	-177.400	-144.209	-0.78	16.683	0.119
Line(2)_c	Lne	10.84	Terminal(18)	161.350	131.281	0.78	15.180	0.108
			Terminal(20)	-161.192	-131.234	-0.78	15.180	0.108
Line(2)_d	Lne	9.92	Terminal(20)	147.519	120.097	0.78	13.892	0.099
			Terminal(22)	-147.349	-120.046	-0.78	13.892	0.099
Line(2)_e	Lne	9.44	Terminal(22)	140.399	113.965	0.78	13.217	0.094
			Terminal(2)	-140.202	-113.906	-0.78	13.217	0.094
Line(20)	Lne	14.95	Terminal(55)	-218.576	-183.807	-0.77	20.926	0.149
			Terminal(76)	218.929	183.912	0.77	20.926	0.149
Line(21)	Lne	29.29	Single Busbar with ..	435.286	361.640	0.77	41.011	0.293
			Terminal(77)	-434.640	-361.449	-0.77	41.011	0.293
Line(21)_a	Lne	28.29	Terminal(77)	419.515	349.208	0.77	39.600	0.283
			Terminal(79)	-418.261	-348.838	-0.77	39.600	0.283
Line(21)_b	Lne	27.82	Terminal(79)	411.493	342.884	0.77	38.944	0.278
			Terminal(81)	-410.687	-342.647	-0.77	38.944	0.278
Line(21)_c	Lne	26.72	Terminal(81)	394.307	329.467	0.77	37.414	0.267
			Terminal(83)	-393.050	-329.096	-0.77	37.414	0.267
Line(21)_d	Lne	26.25	Terminal(83)	386.156	323.053	0.77	36.745	0.262
			Terminal(86)	-385.039	-322.724	-0.77	36.745	0.262
Line(21)_e	Lne	25.88	Terminal(86)	379.907	318.008	0.77	36.236	0.259
			Terminal(76)	-379.573	-317.910	-0.77	36.236	0.259
Line(22)	Lne	0.48	Terminal(83)	6.894	6.043	0.75	0.669	0.005
			Terminal(84)	-6.894	-6.043	-0.75	0.669	0.005
Line(23)	Lne	0.56	Terminal(88)	8.131	6.955	0.76	0.789	0.006

Grid: IlhaGrid	System Stage: IlhaGrid	Study Case: Study Case	Annex: / 6

Name	Type	Loading [%]	Busbar	Active Power [kW]	Reactive Power [kvar]	Power.-factor [-]	Current [A]	Current [p.u.]
			Terminal(89)	-8.131	-6.955	-0.76	0.789	0.006
Line(24)	Lne	0.48	Terminal(93)	6.890	6.021	0.75	0.675	0.005
			Terminal(94)	-6.890	-6.021	-0.75	0.675	0.005
Line(25)	Lne	0.48	Terminal(102)	6.922	6.042	0.75	0.679	0.005
			Terminal(103)	-6.921	-6.042	-0.75	0.679	0.005
Line(26)	Lne	0.50	Terminal(107)	7.129	6.198	0.75	0.698	0.005
			Terminal(108)	-7.129	-6.198	-0.75	0.698	0.005
Line(27)	Lne	1.34	Terminal(112)	20.228	15.282	0.80	1.874	0.013
			Terminal(113)	-20.225	-15.282	-0.80	1.874	0.013
Line(28)	Lne	0.89	Terminal(118)	-13.061	-10.662	-0.77	1.242	0.009
			Terminal(122)	13.061	10.662	0.77	1.242	0.009
Line(28)_a	Lne	2.36	Terminal(119)	-34.240	-29.103	-0.76	3.309	0.024
			Terminal(48)	34.265	29.111	0.76	3.309	0.024
Line(29)	Lne	1.88	Terminal(122)	-27.220	-22.992	-0.76	2.625	0.019
			Terminal(119)	27.245	23.000	0.76	2.625	0.019
Line(3)	Lne	0.45	Terminal	6.960	5.100	0.81	0.626	0.004
			Terminal(3)	-6.960	-5.100	-0.81	0.626	0.004
Line(30)	Lne	0.99	Terminal(122)	14.158	12.330	0.75	1.383	0.010
			Terminal(125)	-14.157	-12.330	-0.75	1.383	0.010
Line(30)_a	Lne	0.49	Terminal(125)	7.051	6.144	0.75	0.689	0.005
			Terminal(124)	-7.050	-6.144	-0.75	0.689	0.005
Line(31)	Lne	0.50	Terminal(125)	7.107	6.186	0.75	0.694	0.005
			Terminal(126)	-7.106	-6.186	-0.75	0.694	0.005
Line(32)	Lne	10.94	Terminal(76)	160.644	133.998	0.77	15.310	0.109
			Terminal(128)	-160.475	-133.948	-0.77	15.310	0.109
Line(33)	Lne	0.49	Terminal(128)	7.077	6.174	0.75	0.688	0.005
			Terminal(129)	-7.077	-6.174	-0.75	0.688	0.005
Line(34)	Lne	10.44	Terminal(128)	153.398	127.774	0.77	14.622	0.104
			Terminal(131)	-153.282	-127.740	-0.77	14.622	0.104
Line(35)	Lne	0.49	Terminal(131)	7.053	6.155	0.75	0.686	0.005
			Terminal(132)	-7.053	-6.155	-0.75	0.686	0.005
Line(36)	Lne	9.95	Terminal(131)	146.229	121.585	0.77	13.937	0.100
			Terminal(137)	-146.092	-121.545	-0.77	13.937	0.100
Line(36)_a	Lne	9.44	Terminal(137)	138.592	115.055	0.77	13.209	0.094
			Terminal(135)	-138.471	-115.019	-0.77	13.209	0.094
Line(36)_b	Lne	8.57	Terminal(135)	125.760	104.614	0.77	12.004	0.086
			Terminal(134)	-125.637	-104.578	-0.77	12.004	0.086
Line(37)	Lne	3.40	Terminal(134)	49.776	41.641	0.77	4.766	0.034
			Terminal(141)	-49.752	-41.634	-0.77	4.766	0.034
Line(37)_a	Lne	2.92	Terminal(141)	42.860	35.604	0.77	4.093	0.029
			Terminal(144)	-42.845	-35.600	-0.77	4.093	0.029
Line(37)_b	Lne	2.44	Terminal(144)	35.954	29.571	0.77	3.421	0.024
			Terminal(147)	-35.949	-29.569	-0.77	3.421	0.024
Line(37)_c	Lne	1.96	Terminal(147)	29.058	23.541	0.78	2.748	0.020
			Terminal(150)	-29.055	-23.540	-0.78	2.748	0.020

Grid: IlhaGrid | System Stage: IlhaGrid | Study Case: Study Case | Annex: / 7

Name	Type	Loading [%]	Busbar	Active Power [kW]	Reactive Power [kvar]	Power.-factor [-]	Current [A]	Current [p.u.]
Line(37)_d	Lne	0.90	Terminal(150)	13.335	10.872	0.78	1.264	0.009
			Terminal(140)	-13.334	-10.872	-0.78	1.264	0.009
Line(38)	Lne	0.48	Terminal(144)	6.892	6.029	0.75	0.673	0.005
			Terminal(145)	-6.891	-6.029	-0.75	0.673	0.005
Line(39)	Lne	0.48	Terminal(147)	6.892	6.029	0.75	0.673	0.005
			Terminal(148)	-6.891	-6.029	-0.75	0.673	0.005
Line(4)	Lne	17.88	Single Busbar with ..	269.435	216.274	0.78	25.038	0.179
			Terminal(175)	-269.330	-216.243	-0.78	25.038	0.179
Line(4)_a	Lne	17.88	Terminal(175)	269.330	216.243	0.78	25.038	0.179
			Terminal(4)	-269.225	-216.212	-0.78	25.038	0.179
Line(40)	Lne	0.36	Terminal(153)	-5.107	-4.688	-0.74	0.510	0.004
			Terminal(159)	5.107	4.688	0.74	0.510	0.004
Line(40)_a	Lne	5.17	Terminal(154)	-75.824	-62.926	-0.77	7.238	0.052
			Terminal(134)	75.861	62.937	0.77	7.238	0.052
Line(41)	Lne	4.01	Terminal(155)	-58.609	-49.142	-0.77	5.620	0.040
			Terminal(154)	58.631	49.148	0.77	5.620	0.040
Line(42)	Lne	2.98	Terminal(156)	-43.330	-36.810	-0.76	4.178	0.030
			Terminal(155)	43.338	36.812	0.76	4.178	0.030
Line(43)	Lne	2.50	Terminal(157)	-36.427	-30.777	-0.76	3.505	0.025
			Terminal(156)	36.439	30.781	0.76	3.505	0.025
Line(44)	Lne	2.14	Terminal(158)	-31.314	-26.087	-0.77	2.996	0.021
			Terminal(157)	31.320	26.089	0.77	2.996	0.021
Line(45)	Lne	1.58	Terminal(159)	-23.276	-19.199	-0.77	2.218	0.016
			Terminal(158)	23.278	19.200	0.77	2.218	0.016
Line(46)	Lne	0.48	Terminal(156)	6.891	6.029	0.75	0.673	0.005
			Terminal(162)	-6.891	-6.029	-0.75	0.673	0.005
Line(47)	Lne	0.36	Terminal(157)	5.107	4.688	0.74	0.510	0.004
			Terminal(164)	-5.107	-4.688	-0.74	0.510	0.004
Line(48)	Lne	4.39	Terminal(100)	64.027	53.217	0.77	6.150	0.044
			Terminal(102)	-64.015	-53.214	-0.77	6.150	0.044
Line(49)	Lne	2.92	Terminal(107)	42.946	34.870	0.78	4.088	0.029
			Terminal(110)	-42.938	-34.868	-0.78	4.088	0.029
Line(5)	Lne	0.49	Terminal(1)	7.079	6.186	0.75	0.684	0.005
			Terminal(11)	-7.079	-6.186	-0.75	0.684	0.005
Line(52)	Lne	4.57	Terminal(173)	67.803	55.225	0.78	6.399	0.046
			Terminal(39)	-67.799	-55.224	-0.78	6.399	0.046
Line(6)	Lne	4.87	Terminal(2)	72.394	58.680	0.78	6.818	0.049
			Terminal(25)	-72.356	-58.669	-0.78	6.818	0.049
Line(6)_a	Lne	3.93	Terminal(25)	58.420	47.337	0.78	5.504	0.039
			Terminal(27)	-58.378	-47.324	-0.78	5.504	0.039
Line(6)_b	Lne	3.13	Terminal(27)	46.515	37.553	0.78	4.378	0.031
			Terminal(23)	-46.505	-37.550	-0.78	4.378	0.031
Line(7)	Lne	0.49	Terminal(23)	7.029	6.138	0.75	0.684	0.005
			Terminal(28)	-7.029	-6.138	-0.75	0.684	0.005
Line(8)	Lne	2.64	Terminal(23)	39.476	31.413	0.78	3.695	0.026

Grid: IlhaGrid | System Stage: IlhaGrid | Study Case: Study Case | Annex: / 8

Name	Type	Loading [%]	Busbar	Active Power [kW]	Reactive Power [kvar]	Power.-factor [-]	Current [A]	Current [p.u.]
			Terminal(32)	-39.471	-31.411	-0.78	3.695	0.026
Line(8)_a	Lne	1.43	Terminal(32)	20.935	17.444	0.77	1.996	0.014
			Terminal(34)	-20.933	-17.443	-0.77	1.996	0.014
Line(8)_b	Lne	0.94	Terminal(34)	13.936	11.330	0.78	1.316	0.009
			Terminal(30)	-13.936	-11.330	-0.78	1.316	0.009
Line(9)	Lne	0.49	Terminal(34)	6.997	6.113	0.75	0.681	0.005
			Terminal(33)	-6.997	-6.113	-0.75	0.681	0.005
1	Tr2	109.34	Terminal(4)	22.018	16.171	0.81	1.981	1.093
			Terminal(47)	-21.148	-15.381	-0.81	118.176	1.087
10	Tr2	10.36	Terminal(27)	11.863	9.771	0.77	1.126	0.104
			Terminal(21)	-11.664	-8.748	-0.80	64.119	0.098
100	Tr2	6.19	Terminal(145)	6.891	6.029	0.75	0.673	0.062
			Terminal(146)	-6.696	-5.022	-0.80	36.920	0.057
101(1)	Tr2	6.19	Terminal(148)	6.891	6.029	0.75	0.673	0.062
			Terminal(149)	-6.696	-5.022	-0.80	36.924	0.057
11	Tr2	93.85	Terminal(32)	18.536	13.967	0.80	1.700	0.939
			Terminal(26)	-17.848	-13.386	-0.80	101.346	0.932
12	Tr2	12.11	Terminal(30)	13.936	11.330	0.78	1.316	0.121
			Terminal(31)	-13.736	-10.302	-0.80	75.546	0.116
13	Tr2	6.17	Terminal(42)	6.893	6.037	0.75	0.671	0.062
			Terminal(36)	-6.696	-5.022	-0.80	36.781	0.056
14	Tr2	88.81	Terminal(44)	17.556	13.210	0.80	1.609	0.888
			Terminal(40)	-16.920	-12.690	-0.80	95.865	0.882
15	Tr2	11.68	Terminal(49)	13.431	10.951	0.78	1.269	0.117
			Terminal(41)	-13.232	-9.924	-0.80	72.752	0.112
16	Tr2	10.69	Terminal(37)	12.255	10.066	0.77	1.162	0.107
			Terminal(43)	-12.056	-9.042	-0.80	66.284	0.102
17	Tr2	34.56	Terminal(3)	6.960	5.100	0.81	0.626	0.346
			Terminal(52)	-6.696	-5.022	-0.80	36.871	0.339
18	Tr2	6.30	Terminal(11)	7.079	6.186	0.75	0.684	0.063
			Terminal(7)	-6.880	-5.160	-0.80	37.582	0.058
19	Tr2	6.29	Terminal(28)	7.029	6.138	0.75	0.684	0.063
			Terminal(24)	-6.832	-5.124	-0.80	37.552	0.058
2	Tr2	10.97	Terminal(8)	12.690	10.408	0.77	1.192	0.110
			Terminal(5)	-12.488	-9.366	-0.80	68.089	0.104
20	Tr2	6.26	Terminal(33)	6.997	6.113	0.75	0.681	0.063
			Terminal(29)	-6.800	-5.100	-0.80	37.383	0.057
21	Tr2	9.38	Terminal(38)	10.710	8.906	0.77	1.019	0.094
			Terminal(35)	-10.512	-7.884	-0.80	57.734	0.089
22	Tr2	6.17	Terminal(51)	6.893	6.036	0.75	0.671	0.062
			Terminal(50)	-6.696	-5.022	-0.80	36.796	0.056
23	Tr2	12.99	Terminal(77)	15.124	12.241	0.78	1.412	0.130
			Terminal(78)	-14.920	-11.190	-0.80	81.264	0.125
24	Tr2	6.03	Terminal(79)	6.768	5.954	0.75	0.655	0.060
			Terminal(80)	-6.568	-4.926	-0.80	35.834	0.055

Grid: IlhaGrid | System Stage: IlhaGrid | Study Case: Study Case | Annex: / 9

Name	Type	Loading [%]	Busbar	Active Power [kW]	Reactive Power [kvar]	Power.-factor [-]	Current [A]	Current [p.u.]
25	Tr2	14.08	Terminal(81)	16.380	13.180	0.78	1.531	0.141
			Terminal(82)	-16.176	-12.132	-0.80	88.433	0.136
26	Tr2	4.69	Terminal(86)	5.133	4.716	0.74	0.510	0.047
			Terminal(87)	-4.936	-3.702	-0.80	27.086	0.042
27	Tr2	4.74	Terminal(55)	5.188	4.755	0.74	0.516	0.047
			Terminal(56)	-4.992	-3.744	-0.80	27.444	0.042
28	Tr2	6.38	Terminal(69)	7.107	6.190	0.75	0.693	0.064
			Terminal(70)	-6.912	-5.184	-0.80	38.144	0.058
29	Tr2	6.18	Terminal(74)	6.866	6.006	0.75	0.672	0.062
			Terminal(75)	-6.672	-5.004	-0.80	36.879	0.057
3	Tr2	11.78	Terminal(10)	13.642	11.122	0.78	1.280	0.118
			Terminal(6)	-13.440	-10.080	-0.80	73.384	0.113
30	Tr2	11.36	Terminal(91)	12.973	10.595	0.77	1.235	0.114
			Terminal(92)	-12.776	-9.582	-0.80	70.717	0.108
31	Tr2	6.42	Terminal(96)	7.130	6.201	0.75	0.697	0.064
			Terminal(97)	-6.936	-5.202	-0.80	38.410	0.059
32	Tr2	6.21	Terminal(98)	6.890	6.019	0.75	0.676	0.062
			Terminal(99)	-6.696	-5.022	-0.80	37.099	0.057
33	Tr2	10.95	Terminal(100)	12.468	10.212	0.77	1.190	0.110
			Terminal(101)	-12.272	-9.204	-0.80	68.049	0.104
34	Tr2	6.31	Terminal(105)	6.993	6.096	0.75	0.686	0.063
			Terminal(106)	-6.800	-5.100	-0.80	37.705	0.058
35	Tr2	7.57	Terminal(110)	8.474	7.208	0.76	0.822	0.076
			Terminal(111)	-8.280	-6.210	-0.80	45.930	0.070
36	Tr2	6.40	Terminal(115)	7.105	6.180	0.75	0.696	0.064
			Terminal(116)	-6.912	-5.184	-0.80	38.340	0.059
37	Tr2	6.42	Terminal(54)	7.129	6.197	0.75	0.698	0.064
			Terminal(117)	-6.936	-5.202	-0.80	38.476	0.059
38	Tr2	6.16	Terminal(84)	6.894	6.043	0.75	0.669	0.062
			Terminal(85)	-6.696	-5.022	-0.80	36.671	0.056
39	Tr2	6.12	Terminal(60)	6.812	5.971	0.75	0.665	0.061
			Terminal(58)	-6.616	-4.962	-0.80	36.438	0.056
4	Tr2	12.14	Terminal(14)	14.058	11.432	0.78	1.320	0.121
			Terminal(12)	-13.856	-10.392	-0.80	75.766	0.116
40	Tr2	12.11	Terminal(63)	13.911	11.308	0.78	1.316	0.121
			Terminal(61)	-13.712	-10.284	-0.80	75.577	0.116
41	Tr2	7.30	Terminal(65)	8.212	7.021	0.76	0.794	0.073
			Terminal(64)	-8.016	-6.012	-0.80	44.203	0.068
42	Tr2	7.82	Terminal(68)	8.820	7.477	0.76	0.850	0.078
			Terminal(67)	-8.624	-6.468	-0.80	47.590	0.073
43	Tr2	6.45	Terminal(73)	7.187	6.248	0.75	0.701	0.064
			Terminal(72)	-6.992	-5.244	-0.80	38.621	0.059
44	Tr2	7.25	Terminal(89)	8.131	6.955	0.76	0.789	0.073
			Terminal(90)	-7.936	-5.952	-0.80	43.893	0.067
45	Tr2	6.21	Terminal(94)	6.890	6.021	0.75	0.675	0.062

Grid: IlhaGrid | System Stage: IlhaGrid | Study Case: Study Case | Annex: / 10

Name	Type	Loading [%]	Busbar	Active Power [kW]	Reactive Power [kvar]	Power.-factor [-]	Current [A]	Current [p.u.]
			Terminal(95)	-6.696	-5.022	-0.80	37.064	0.057
46	Tr2	6.25	Terminal(103)	6.921	6.042	0.75	0.679	0.062
			Terminal(104)	-6.728	-5.046	-0.80	37.300	0.057
47	Tr2	6.42	Terminal(108)	7.129	6.198	0.75	0.698	0.064
			Terminal(109)	-6.936	-5.202	-0.80	38.466	0.059
48	Tr2	103.44	Terminal(113)	20.225	15.282	0.80	1.874	1.034
			Terminal(114)	-19.433	-14.575	-0.80	111.781	1.028
49	Tr2	6.29	Terminal(119)	6.995	6.103	0.75	0.683	0.063
			Terminal(120)	-6.800	-5.100	-0.80	37.570	0.058
5	Tr2	11.72	Terminal(16)	13.545	11.045	0.78	1.274	0.117
			Terminal(17)	-13.344	-10.008	-0.80	73.030	0.112
50	Tr2	11.43	Terminal(118)	13.061	10.662	0.77	1.242	0.114
			Terminal(121)	-12.864	-9.648	-0.80	71.151	0.109
51	Tr2	6.34	Terminal(124)	7.050	6.144	0.75	0.689	0.063
			Terminal(123)	-6.856	-5.142	-0.80	37.908	0.058
52	Tr2	6.39	Terminal(126)	7.106	6.186	0.75	0.694	0.064
			Terminal(127)	-6.912	-5.184	-0.80	38.217	0.059
6	Tr2	13.84	Terminal(18)	16.051	12.928	0.78	1.504	0.138
			Terminal(9)	-15.848	-11.886	-0.80	86.831	0.133
7	Tr2	11.85	Terminal(20)	13.673	11.138	0.78	1.288	0.118
			Terminal(13)	-13.472	-10.104	-0.80	73.856	0.113
8	Tr2	6.21	Terminal(22)	6.950	6.082	0.75	0.675	0.062
			Terminal(15)	-6.752	-5.064	-0.80	37.032	0.057
86	Tr2	6.69	Terminal(137)	7.500	6.490	0.76	0.727	0.067
			Terminal(139)	-7.304	-5.478	-0.80	40.194	0.062
87(1)	Tr2	11.09	Terminal(135)	12.710	10.405	0.77	1.205	0.111
			Terminal(136)	-12.512	-9.384	-0.80	68.921	0.106
88	Tr2	14.89	Terminal(154)	17.193	13.777	0.78	1.618	0.149
			Terminal(160)	-16.992	-12.744	-0.80	93.726	0.144
89(1)	Tr2	13.27	Terminal(155)	15.271	12.330	0.78	1.442	0.133
			Terminal(161)	-15.072	-11.304	-0.80	83.148	0.127
9	Tr2	12.10	Terminal(25)	13.936	11.332	0.78	1.315	0.121
			Terminal(19)	-13.736	-10.302	-0.80	75.479	0.116
90	Tr2	7.16	Terminal(158)	8.036	6.888	0.76	0.778	0.072
			Terminal(166)	-7.840	-5.880	-0.80	43.253	0.066
91(1)	Tr2	15.73	Terminal(159)	18.169	14.511	0.78	1.710	0.157
			Terminal(167)	-17.968	-13.476	-0.80	99.200	0.152
92	Tr2	4.69	Terminal(153)	5.107	4.688	0.74	0.510	0.047
			Terminal(168)	-4.912	-3.684	-0.80	27.097	0.042
93(1)	Tr2	6.33	Terminal(129)	7.077	6.174	0.75	0.688	0.063
			Terminal(130)	-6.880	-5.160	-0.80	37.813	0.058
94	Tr2	6.31	Terminal(132)	7.053	6.155	0.75	0.686	0.063
			Terminal(133)	-6.856	-5.142	-0.80	37.702	0.058
95(1)	Tr2	6.19	Terminal(162)	6.891	6.029	0.75	0.673	0.062
			Terminal(163)	-6.696	-5.022	-0.80	36.925	0.057

Grid: IlhaGrid	System Stage: IlhaGrid		Study Case: Study Case			Annex:		/ 11
Name	Type	Loading [%]	Busbar	Active Power [kW]	Reactive Power [kvar]	Power.-factor [-]	Current [A]	Current [p.u.]
96	Tr2	4.69	Terminal(164)	5.107	4.688	0.74	0.510	0.047
			Terminal(165)	-4.912	-3.684	-0.80	27.091	0.042
97(1)	Tr2	6.19	Terminal(141)	6.892	6.030	0.75	0.673	0.062
			Terminal(143)	-6.696	-5.022	-0.80	36.910	0.057
98	Tr2	13.65	Terminal(150)	15.720	12.667	0.78	1.484	0.136
			Terminal(151)	-15.520	-11.640	-0.80	85.636	0.131
99(1)	Tr2	11.63	Terminal(140)	13.334	10.872	0.78	1.264	0.116
			Terminal(152)	-13.136	-9.852	-0.80	72.474	0.111
Equivalent Transformer	Tr2	0.00	Single Busbar with ..	0.000	0.000	1.00	0.000	0.000
			Terminal(171)	0.000	0.000	1.00	0.000	0.000
Switch	Switch	0.00	Terminal(48)	0.000	0.000	1.00	0.000	0.000
			Low-Voltage Load(1)	0.000	0.000	1.00	0.000	0.000
Switch	Switch	0.00	Terminal(76)	0.000	0.000	1.00	0.000	0.000
			Low-Voltage Load	0.000	0.000	1.00	0.000	0.000

CHAPTER E. RELIABILITY ANALYSIS RESULTS

This chapter presents a sample of a reliability analysis result for the original power system, without any DERs in the network. Each table provides the reliability analysis results for one component in the network. The first table shows the result for transformer 1, the second table shows the result for Line(1) and the third shows the result for Terminal(101). The first three tables present the details about each component such as repair duration, failure frequency, summery of the failure effect and the contingency description. The interruption cost was not considered in this simulation.

Subsection E.2 presents the reliability analysis summery of the entire power system. The load flow analysis is the reliability analysis method used. Contingency definition was generated automatically by considering whole system. System summery provides the parameters discussed in section 4.2.1.5 and more, which are self descriptive.

E.1 Reliability analysis without DERs: sample outputs

		DIgSILENT PowerFactory	Project:

Contingency: 1

Fault location (n-1):
Component: 1 — 2-Winding Transformer
Network: IlhaGrid

Repair Duration: 15.00 h (900 min)
Failure frequency: 0.020 1/a

Summary of failure effects

	Power	Customers
Interrupted:	323.3 kW	41
Restored:	0.0 kW (0.0 %)	0 (0.0 %)
Energy not supplied	4850.2 kWh	

	1/failure	Yearly	Yearly (load state)
Interruption costs:	0.0 k$	0.000 k$/a	*100.00 % = 0.000 k$/a

Time [min]	Step	Action	Device	Station:	
0:00	Protection	Open	CB.L2	Single Bus	
					Interrupted: 323.3 kW
30:00	Short Circuit Indicator	Open	Switch		
30:00		Open	Switch		
30:00		Open	Switch		
30:00		Open	Switch		
30:00		Open	Switch		
30:00		Open	Switch		
30:00		Open	Switch		
30:00		Open	Switch		
30:00		Open	Switch		
30:00		Open	Switch		
30:00		Open	Switch		
30:00		Open	Switch		
30:00		Open	Switch		
30:00		Open	Switch		
30:00		Open	Switch		
30:00		Open	Switch		
30:00		Open	Switch		
30:00		Open	Switch		
30:00		Open	Switch		
30:00		Open	Switch		
30:00		Open	Switch		
30:00		Open	Switch		
30:00	Manual	Open	IS.L2.1	Single Bus	
30:00		Close	CB.L2	Single Bus	
					Interrupted: 323.3 kW

```
Contingency:    Line(1)

Fault location (n-1):
   Component:       Line(1)          Line
   Network:         IlhaGrid

   Repair Duration:                 10.00 h   (600 min)
   Failure frequency:                0.009 1/a

Summary of failure effects
                                      Power                          Customers
  Interrupted:                       323.3 kW                           41
  Restored:                            0.0 kW (   0.0 %)                 0 (   0.0 %)
  Energy not supplied               3233.5 kWh

                                    1/failure                        Yearly          Yearly (load state)
  Interruption costs:                  0.0 k$                        0.000 k$/a    *100.00 % = 0.000 k$/a

 Time [min]         Step             Action     Device         Station:
    0:00  Protection                 Open       CB.L2          Single Bus
 - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - -   - - - - - - - - - - - - - - - - - - - - - - - - - -
                                                                           Interrupted:                      323.3 kW

   30:00  Short Circuit Indicator    Open       Switch
   30:00                             Open       Switch
   30:00                             Open       Switch
   30:00                             Open       Switch
   30:00                             Open       Switch
   30:00                             Open       Switch
   30:00                             Open       Switch
   30:00                             Open       Switch
   30:00                             Open       Switch
   30:00                             Open       Switch
   30:00                             Open       Switch
   30:00                             Open       Switch
   30:00                             Open       Switch
   30:00                             Open       Switch
   30:00                             Open       Switch
   30:00                             Open       Switch
   30:00                             Open       Switch
   30:00                             Open       Switch
   30:00                             Open       Switch
   30:00                             Open       Switch
   30:00                             Open       Switch
   30:00                             Open       Switch
   30:00  Manual                     Open       IS.L2.1        Single Bus
   30:00                             Close      CB.L2          Single Bus
 - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - -   - - - - - - - - - - - - - - - - - - - - - - - - - -
                                                                           Interrupted:                      323.3 kW
                                                                           Restored Power:                     0.0 kW (  0.0 %)
                                                                           Restored Customers:                 0      (  0.0 %)
                                                                           Totally Restored Power:             0.0 kW (  0.0 %)
                                                                           Totally Restored Customers:         0      (  0.0 %)
                                                                           ENS:(0:00 - 30:00)                161.7 kWh
                                                                           Total ENS:                        161.7 kWh

  600:00  Repair:
 - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - -   - - - - - - - - - - - - - - - - - - - - - - - - - -
                                                                           ENS:(30:00 - 600:00)             3071.8 kWh
                                                                           Total ENS:                       3233.5 kWh
```

```
Contingency:    Terminal(101)

Fault location (n-1):
   Component:       Terminal(101)    Terminal
   Network:         IlhaGrid

   Repair Duration:                 10.00 h   (600 min)
   Failure frequency:                0.018 1/a

Summary of failure effects
                                      Power                          Customers
  Interrupted:                        14.4 kW                            2
  Restored:                            0.0 kW (   0.0 %)                 0 (   0.0 %)
  Energy not supplied                144.3 kWh

                                    1/failure                        Yearly          Yearly (load state)
  Interruption costs:                  0.0 k$                        0.000 k$/a    *100.00 % = 0.000 k$/a

 Time [min]         Step             Action     Device         Station:
    0:00  Protection                 Open       Switch
 - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - -   - - - - - - - - - - - - - - - - - - - - - - - - - -
                                                                           Interrupted:                       14.4 kW

   30:00  Short Circuit Indicator    Open       Switch
   30:00                             Open       Switch
 - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - -   - - - - - - - - - - - - - - - - - - - - - - - - - -
                                                                           Interrupted:                       14.4 kW
                                                                           Restored Power:                     0.0 kW (  0.0 %)
                                                                           Restored Customers:                 0      (  0.0 %)
                                                                           Totally Restored Power:             0.0 kW (  0.0 %)
                                                                           Totally Restored Customers:         0      (  0.0 %)
                                                                           ENS:(0:00 - 30:00)                  7.2 kWh
                                                                           Total ENS:                          7.2 kWh

  600:00  Repair:
 - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - -   - - - - - - - - - - - - - - - - - - - - - - - - - -
                                                                           ENS:(30:00 - 600:00)              137.1 kWh
                                                                           Total ENS:                        144.3 kWh
```

E.2 System summery of the reliability analysis

	Restored Power: 0.0 kW (0.0 %) Restored Customers: 0 (0.0 %) Totally Restored Power: 0.0 kW (0.0 %) Totally Restored Customers: 0 (0.0 %) ENS:(0:00 - 30:00) 161.7 kWh Total ENS: 161.7 kWh
900:00 Repair: -	- ENS:(30:00 - 900:00) 4688.5 kWh Total ENS: 4850.2 kWh

		15.1.7	Date: 1/24/2016

```
Reliability Assessment
  Method                                   Load flow analysis

  Calculation time period                  7/30/2015 11:40:58 PM
  Consider Maintenance                     No
  Fault Clearance Breakers                 Use all circuit breakers
  Switching procedures                     Concurrently
  Consider Sectionalizing (Stages 1-3)     Yes
  Time to open remote controlled switches  1.00 min.

Automatic Contingency Definition
  Selection                                Whole System
  Busbars / terminals                      Yes                Common mode                            No
  Lines / cables                           Yes                Independent second failures            No
  Transformers                             Yes                Double earth faults                    Yes
                                                              Protection/switching failures          No
```

Study Case: Study Case	Annex: / 1

System Summary

```
System Average Interruption Frequency Index        :  SAIFI  =    0.730862 1/Ca
Customer Average Interruption Frequency Index      :  CAIFI  =    0.730862 1/Ca
System Average Interruption Duration Index         :  SAIDI  =    8.995    h/Ca
Customer Average Interruption Duration Index       :  CAIDI  =   12.307    h
Average Service Availability Index                 :  ASAI   =    0.9989732009
Average Service Unavailability Index               :  ASUI   =    0.0010267991
Energy Not Supplied                                :  ENS    =    7.152    MWh/a
Average Energy Not Supplied                        :  AENS   =    0.071    MWh/Ca
Average Customer Curtailment Index                 :  ACCI   =    0.168    MWh/Ca
Expected Interruption Cost                         :  EIC    =    0.000    M$/a
Interrupted Energy Assessment Rate                 :  IEAR   =    0.000    $/kWh
System energy shed                                 :  SES    =    0.000    MWh/a
Average System Interruption Frequency Index        :  ASIFI  =    0.724350 1/a
Average System Interruption Duration Index         :  ASIDI  =    8.912191 h/a
Momentary Average Interruption Frequency Index     :  MAIFI  =    0.000000 1/Ca
```

CHAPTER F. POWER SYSTEM MODELING DETAILS

This chapter provides the sample AutoCAD diagrams of Etrela da Ellha, provided by the ELECTRO. These diagrams contains the details of the modeled power system.

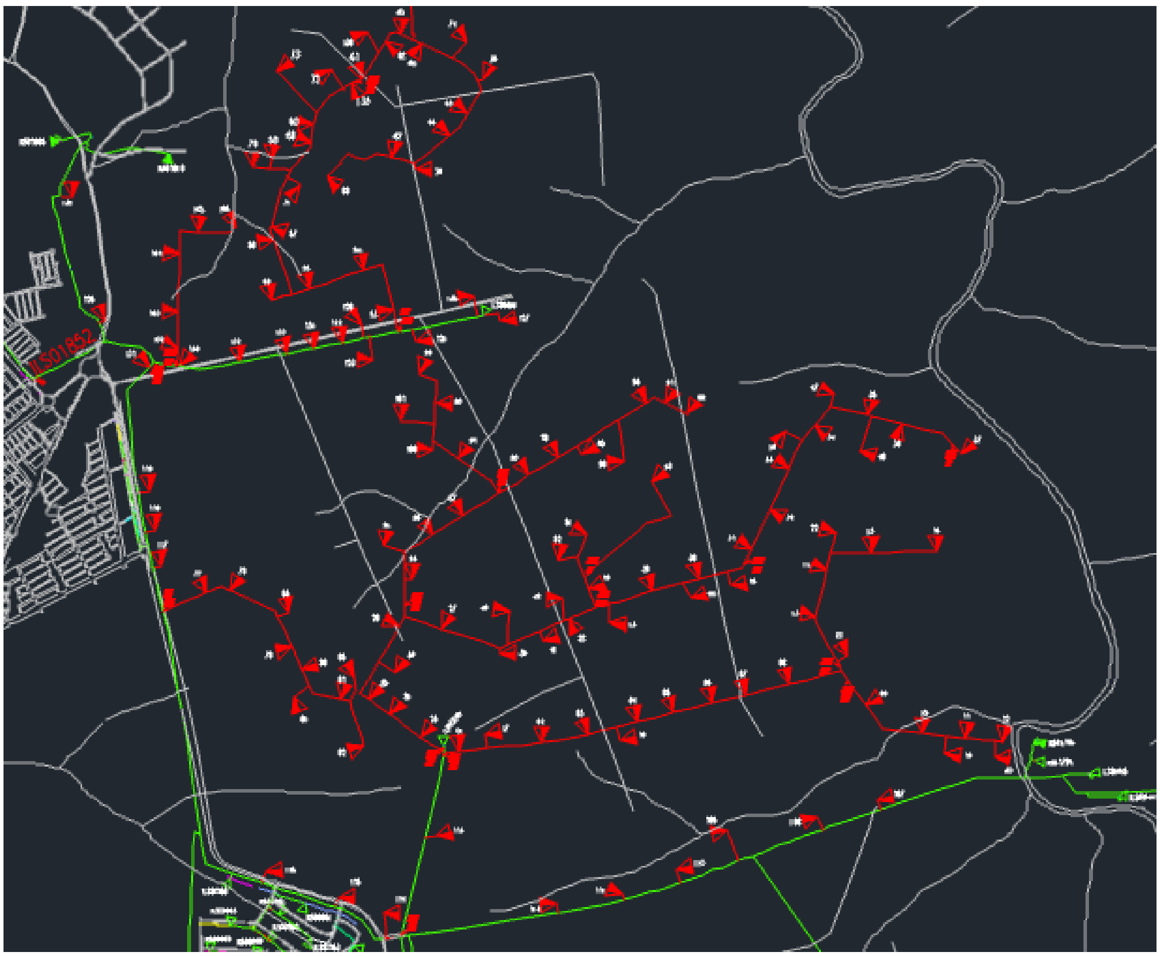


Figure F.1. Complete electrical network

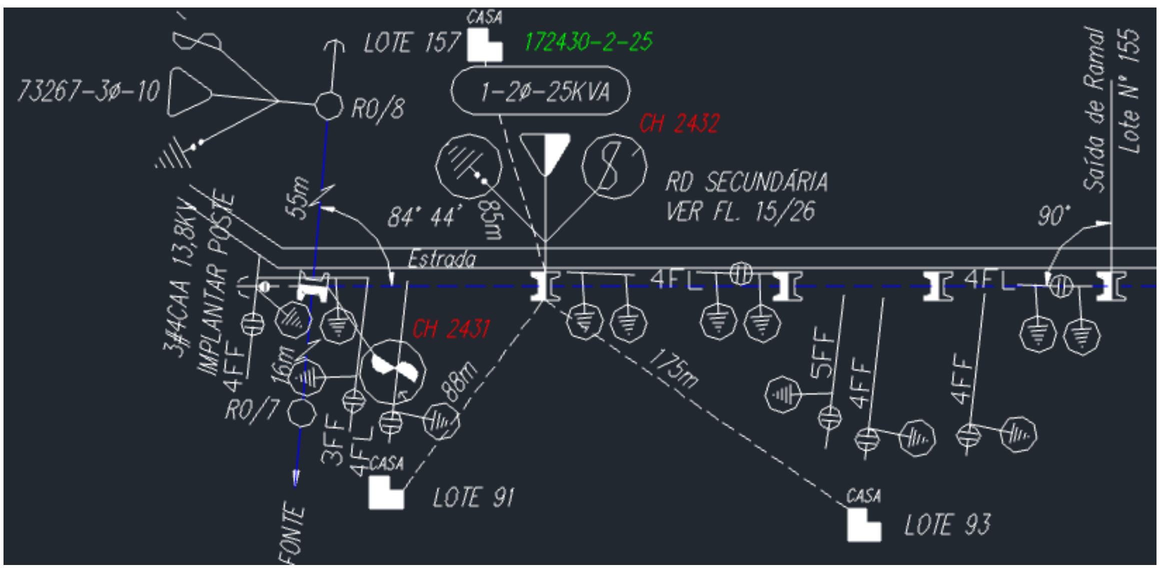


Figure F.2. Example distribution line with connected components

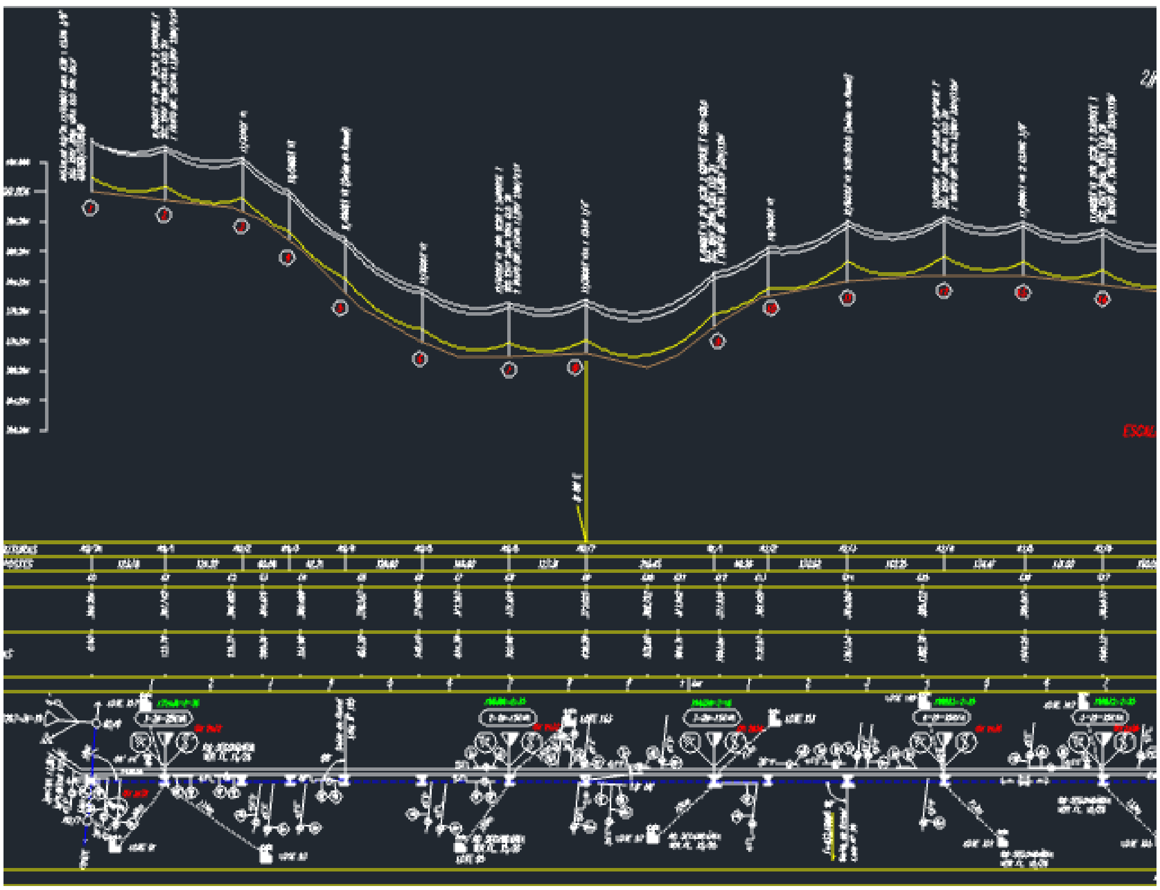


Figure F.3. Example connection of load points

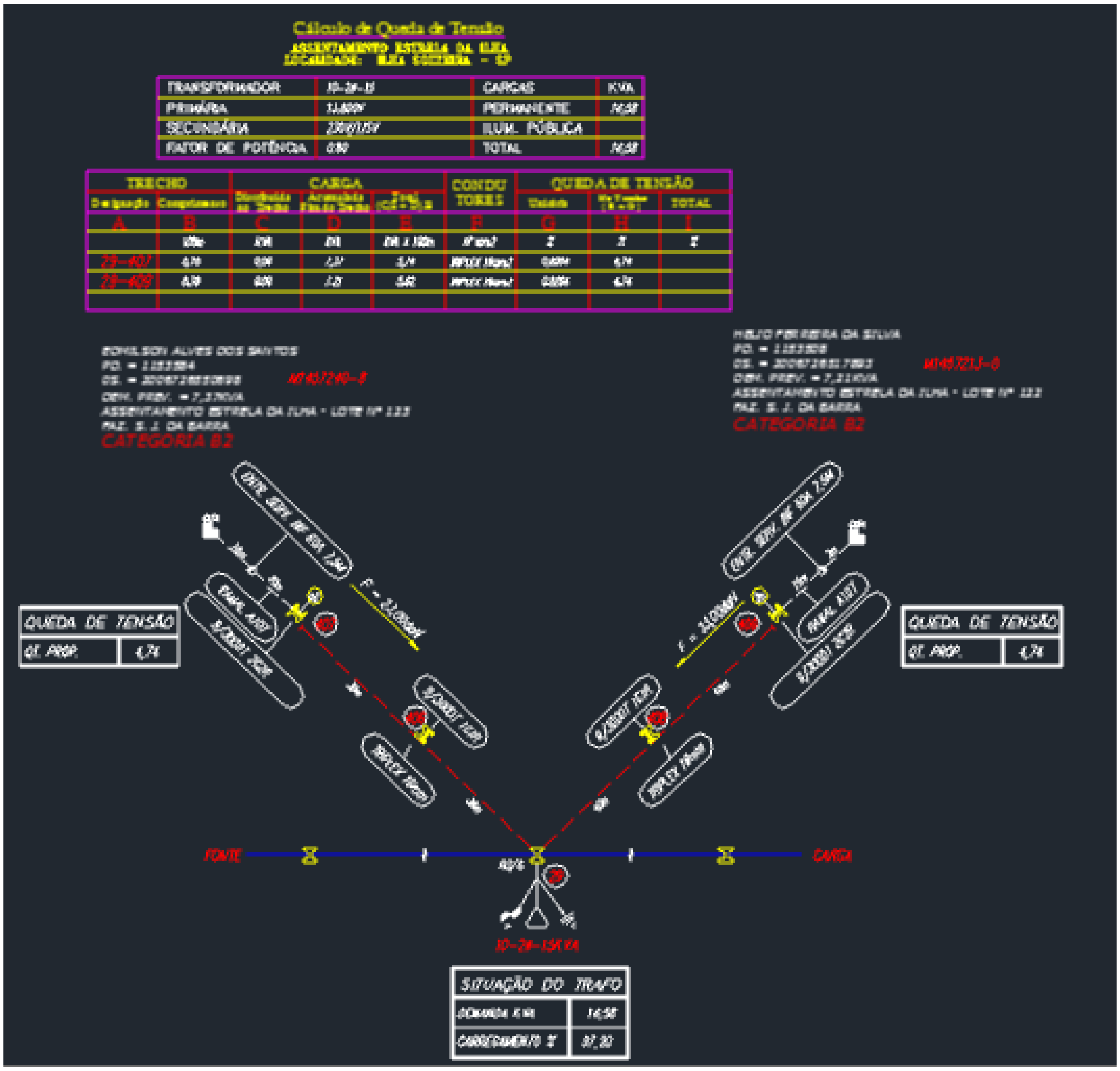


Figure F.4. Example load point details

LIST OF REFERENCES

LIST OF REFERENCES

Ahmad, A. A., & Hussein, E. M. (2014). Electrical Distribution Reliability. *International Journal of Innovative Research in Science, Engineering and Technology*, *9*, 16191 – 16198.

Alfaro, J. F., & Miller, S. a. (2011). Planning the Development of Electricity Grids in Developing Countries : An Initial Approach Using Agent Based Models. *International Symposium on Sustainable Systems and Technology (ISSST) IEEE*, *48103*.

Araneda, J. C., & Ríos, S. (2005). Transmission expansion under market conditions: The Chilean experience. *2005 IEEE Russia Power Tech, PowerTech.* doi: 10.1109/PTC.2005.4524800

Argonne National Laboratory, & Lawrence Berkeley National Laboratoy. (2010). An Overview and Summary of Capabilities of the Stochastic Energy Deployment System (SEDS) Model.

Bebic, J. (2008). *Power System Planning: Emerging Practices Suitable for Evaluating the Impact of High-Penetration Photovoltaics* (Tech. Rep.). National Renewable Energy Laboratory (NREL). doi: 10.2172/924647

Bellifemine, F., Caire, G., & Greenwood, D. (2007). Developing multi-agent systems with jade. In *Wiley Series in Agent Technology.*

Black & Veatch. (2010). Levelized Cost of Energy Calculation Methodology and Sensitivity. *The China Systainable Energy Program*, 1–16. Retrieved from `http://www.efchina.org/csepupfiles/report/20112844913435.70772110666485.pdf/Levelized Cost of Energy Calculation_BV_EN.pdf`

Borges, C. L. T., & Falco, D. M. (2006). Optimal distributed generation allocation for reliability, losses, and voltage improvement. *International Journal of Electrical Power and Energy Systems*, *28*(6), 413-420. doi: 10.1016/j.ijepes.2006.02.003

Butt, R. (2011). *Microgrid Planning and Design MCAS Miramar , US Air Force Academy , and Fort Carson.* Retrieved from `http://e2s2.ndia.org/schedule/Documents/Abstracts/Butt.pdf`

Chen, Y., Cheng, & Hoff, S. (n.d.). Modeling the Variation of Wind Speed with Height for Agricultural Source Pollution Control. , *4*(1), 0–6.

Cochran, J., Mai, T., & Bazilian, M. (2014). Meta-Analysis of High-Penetration Renewable Energy Scenariose. *Renewable and Sustainable Energy Reviews 29*, 246–53.

Cole, W., Mai, T., Steinberg, K. E. D. C., & Margolis, R. (2015). "Considering the Role of Solar Generation under Rate-Based Targets in the EPA's Proposed Clean Power Plan. In *Energy policy institute's fifth annual energy policy research conference* (pp. 20–28). doi: 10.1016/j.tej.2015.09.002

Contreras, J., & Wu, F. F. (2000). A kernel-oriented algorithm for transmission expansion planning. *IEEE Transactions on Power Systems*, *15*(4), 1434–1440. doi: 10.1109/59.898124

DIgSILENT. (2014). Reliability Analysis. In *Powerfactory 15: User manual* (pp. 687–718). Retrieved from `http://www.digsilent.de`

Ding, M., & Luo, K. (2014). A multi-agent energy coordination control strategy in microgrid island mode. *Lecture Notes in Electrical Engineering*, *238 LNEE*(11511075), 529–536. doi: 10.1007/978-1-4614-4981-2-58

Dios, R., Soto, F., & Conejo, A. J. (2007, August). Planning to expand? *IEEE Power and Energy Magazine*(october), 64–70. doi: 10.1109/MPE.2007.904764

DNV-GL. (n.d.). *Renewable Energy Software.* Retrieved 28 sep 2015, from `https://www.dnvgl.com/energy/generation/software/index.html`

DOE. (2012). *Summary Report : 2012 DOE Microgrid Workshop* (Tech. Rep.). Retrieved from `http://energy.gov/sites/prod/files/2012 Microgrid Workshop Report 09102012.pdf`

Elamine, D. O. (2014). Multi-agent architecture for smart micro-grid optimal control using a hybrid BP-PSO algorithm for wind power prediction.

Elektro. (n.d.). Retrieved 2015-09-2, from `http://www.elektro.com.br/`

EPRI — Distributed Energy Resources. (n.d.). Retrieved 2015-03-15, from `http://www.epri.com/Our-Work/Pages/Distributed-Electricity-Resources.aspx`

Ferguson, I. A. (1992, December). Toward an architecture for adaptive, rational, mobile agents (abstract). *SIGOIS Bull.*, *13*(3), 15–. Retrieved from `http://doi.acm.org/10.1145/152683.152699` doi: 10.1145/152683.152699

Ferreira, A., Leitão, P., & Vrba, P. (2014). Managing Intelligent Self-Sustained Electrical. , 526–531.

Gerdes, K., Summers, W. M., & Wimer, J. (2011). Cost Estimation Methodology for NETL Assessments of Power Plant Performance. DOE/NETL-2011/1455.

Giraldez, J. (2012). *Energy Security : Microgrid Planning and Design.* Retrieved from `http://www.nrel.gov/docs/fy12osti/54985.pdf`

Gnansounou, E., Dong, J., Pierre, S., & Quintero, A. (2004). Market oriented planning of power generation expansion using agent-based model. *Power Systems Conference and Exposition, 2004*(0041), 1306 – 1311 vol.3.

He, Y., & Sharma, R. (2013). Microgrid Generation Expansion Planning Using Agent-Based Simulation. In *Ieee pes innovative smart grid technologies (isgt)* (pp. 1–6). Washington, DC. doi: 10.1109/ISGT.2013.6497868

Himoff, J., Skobelev, P., & Wooldridge, M. (2005). Magenta Technology: Multi-agent Systems for Industrial Logistics. In *4th international conference on autonomous agents and multiagent systems* (pp. 60–66).

Home power. (2010). *Sizing a Grid-Tied PV System ...with Battery Backup.* Retrieved 2016-08-20, from `http://www.homepower.com/articles/solar-electricity/design-installation/sizing-grid-tied-pv-system-battery-backup`

HOMER Energy. (n.d.). Retrieved 2015-10-02, from `http://www.homerenergy.com/software.html`

IEEE. (2001). 1366-2001 - IEEE Guide for Electric Power Distribution Reliability Indices.

International Finance Corporation. (2012). *Utility Scale Solar Power Plants, A Guide For developers And investors.*

Kraus, S., & Grosz, B. (1996). Collaborative plans for complex group action. *Artificial Intelligence*, *08*(02), 269357. doi: 10.1016/0004-3702(95)00103-4

Local United. (2011). *Community-led wind power: How to plan, build and own a medium or large wind turbine in your communitys backyard* (Tech. Rep.).

Mai, T., Hand, M., Baldwin, S., Wiser, R., Brinkman, G., Denholm, P., . . . Bazilian, M. (2014). Renewable Electricity Futures for the United States. *IEEE Transactions on Sustainable Energy*, *5*(2), 372–378.

Map Windows OSS. (2013). *MapWindow GIS 4.8.8.1.* Mao Window GIS. Retrieved from `http://www.mapwindow.org/`

Martin Kurtovich and Marzia Zafar. (2016). *California Electric Reliability Investor-Owned Utilities Performance Review 2006-2015* (Tech. Rep.).

Maturana, F. P., Staron, R., Hall, K., Tichý, P., Šlechta, P., & Maík, V. (2004). An Intelligent Agent Validation Architecture for Distributed Manuf acturing Organizations. *Emerging Solutions for Future Manufacturing Systems*, *159*, 81–90.

McArthur, S. D. J., Davidson, E. M., Catterson, V. M., Dimeas, A. L., Hatziargyriou, N. D., Ponci, F., & Funabashi, T. (2007a). Multi-Agent Systems for Power Engineering ApplicationsPart 1: Concepts, Approaches, and Technical Challenges. *IEEE TRANSACTIONS ON POWER SYSTEMS*, *22*, 1753–1759.

McArthur, S. D. J., Davidson, E. M., Catterson, V. M., Dimeas, a. L., Hatziargyriou, N. D., Ponci, F., & Funabashi, T. (2007b). Multi-Agent Systems for Power Engineering Applications; Part II: Technologies, Standards, and Tools for Building Multi-agent Systems. *Power Systems, IEEE Transactions on*, *22*(4), 1753–1759. doi: 10.1109/TPWRS.2007.908472 *meteoblue.* (n.d.). Retrieved 2015-09-2, from https://www.meteoblue.com/en/weather/forecast/week/ilha-solteira_brazil_3461411

meteoblue. (n.d.). *meteoblueapi.* Retrieved 2015-09-2, from https://content.meteoblue.com/en/products/meteoblue-api

Mfiller, J. P., Pischel, M., & Thiel, M. (1995). Modelling reactive behaviour in vertically layered agent architectures. *Intelligent Agents: Theories, Architectures, and Languages (LNAI 890)*, 261276.

Microgrid Institute. (2015). *About Microgrids.* Retrieved from http://www.microgridinstitute.org/about-microgrids.html

MyGeoData. (2014). *MyGeoData - GIS Data Converter.* Retrieved 10-15-2015, from http://converter.mygeodata.eu/

Navaratne, U. S., Kulatunga, N. A., Redmond, M., & Sampaio, D. B. J. (2015). Automated data collection system for performance analysis of home appliances under Conservation Voltage Reduction (CVR). In *In the xi latin-american congress electricity generation and transmission.*

NREL. (2014). *Regional Energy Deployment System (ReEDS).* Retrieved 2014-10-10, from http://www.nrel.gov/analysis/reeds/

NREL. (2015). *National Solar Radiation Data Base.* Retrieved 2015-08-25, from http://rredc.nrel.gov/solar/old_data/nsrdb/

Ochoa, L. F., & Harrison, G. P. (2011). Minimizing energy losses: Optimal accommodation and smart operation of renewable distributed generation. *IEEE Transactions on Power Systems*, *26*(1), 198–205. doi: 10.1109/TPWRS.2010.2049036

Oklahoma Cooperative Extension Service. (n.d.). Wind Energy Leasing Handbook. *Oklahoma Cooperative Extension Service Division of Agricultural Sciences and Natural Resources Oklahoma State University*.

Oliveira, P., Pinto, T., Praca, I., Vale, Z., & Morais, H. (2013). Intelligent micro grid management using a multi-agent approach. *2013 IEEE Grenoble Conference PowerTech, POWERTECH 2013*. doi: 10.1109/PTC.2013.6652263

Oyarzabal, J., Jimeno, J., Ruela, J., Engler, a., & Hardt, C. (2005). Agent based micro grid management system. *2005 International Conference on Future Power Systems*, 1–6. doi: 10.1109/FPS.2005.204230

Panait, L., & Luke, S. (2005). Cooperative multiagent learning: the state of the art. *Autonomous Agents and Multi-Agent Systems*, *11*(03), 387-434. doi: 10.1016/0004-3702(95)00103-4

Pavlos, S., & Nikos, D. H. (2015). A review of power distribution planning in the modern power systems era: Models, methods and future research. *Electric Power System Research*, *121*(3), 89–100.

Prakash, O. K. S., Rajasekaran, P., & Veerappan, N. (2012). Effective micro grid control in a smart grid environment using IP based multiagent technology. *Proceedings - ICETEEEM 2012, International Conference on Emerging Trends in Electrical Engineering and Energy Management*, 293–298. doi: 10.1109/ICETEEEM.2012.6494504

Qiao, L. (2013). A Summary of Optimal Methods for the Planning of Stand-alone Microgrid System. *Energy and Power Engineering*, *05*(04), 992–998. doi: 10.4236/epe.2013.54B190

Rao, A. S., & Georgeff, M. P. (1995). Bdi agents: From theory to practice. In *In proceedings of the first international conference on multi-agent systems (icmas-95* (pp. 312–319).

Roberts, J., Cassula, A. M., & Hauer, I. (2014). Electricity consumption characterization of different end-use sectors of Brazil. In *Consumer control in smart grids second elecon workshop* (pp. 43–56).

Schild, K., & Bussmann, S. (2007, dec). Self-organization in manufacturing operations. *Communications of the ACM*, *50*(12), 74–79.

Shehory, O., & Sturm, A. (2014). *Agent-Oriented Software Engineering: Reflections on Architectures, Methodologies, Languages, and Frameworks.* Springer-Verlag Berlin Heidelberg.

Smith, M. (2011). U.S. Department of Energys Research & Development Activities on Microgrid Technologies. In *Jeju 2011 symposium on microgrids.* Retrieved from `https://der.lbl.gov/sites/der.lbl.gov/files/jeju_smith.pdf`

SPADE. (n.d.). *SPADE 2.2.1 : Python Package Index.* Retrieved 2015-03-03, from `https://pypi.python.org/pypi/SPADE`

Su, W., Yuan, Z., & Chow, M. Y. (2010). Microgrid planning and operation: Solar energy and wind energy. In *Ieee pes general meeting, pes 2010.* doi: 10.1109/PES.2010.5589391

United State Nuclear Regulatory Commission. (2015). *Capacity factor (net).* Retrieved from `http://www.nrc.gov/reading-rm/basic-ref/glossary/capacity-factor-net.html`

University of York. (2009). *MACSimJX - Software enabling MATLAB to operate with JADE (the Java Agent Development Environment) -.* Retrieved 2015-03-11, from `http://www.mathworks.com/matlabcentral/linkexchange/links/1940-macsimjx-software-enabling-matlab-to-operate-with-jade-the-java-agent-development-environment`

Wang, Z., Yang, R., & Wang, L. (2011). Intelligent multi-agent control for integrated building and micro-grid systems. *IEEE PES Innovative Smart Grid Technologies Conference Europe, ISGT Europe*, *43606*, 1–7. doi: 10.1109/ISGT.2011.5759134

Wilcox, S. (2012). National Solar Radiation Database 1991 2010 Update : User s Manual. (August), 479. Retrieved from http://www.nrel.gov/docs/fy12osti/54824.pdf doi: 10.2172/901864

Willis, H. L. (2004). Power Distribution Planning Reference Book, Second Edition. , 1248. Retrieved from http://books.google.com/books?hl=en&lr=&id=9EShPwTRnoUC&pgis=1

WINDUSTRY. (2015). *Wind Resource and Speeds.* Retrieved from http://www.windustry.org/wind_resource_and_speeds

Wooldridge, M. (2002). *An Introduction to Multiagent Systems* (1st ed.). John Wiley & Sons Ltd, West Sussex, England.

VITA

VITA

Uditha Sudheera Navaratne was born in Peradeniya, Sri Lanka on 04 April 1982. After finishing his studies at Dharmaraja collage, Kandy, Sri Lanka he went on to the University of Peradeniya, Sri Lanka where he studied electrical and electronic engineering and received his Bachelor of Science in August 2007. For next three years he pursued his carrier as an engineer in Sri Lanka Telecom and as a lecturer in University of Peradeniya. He moved to USA on January 2011 and entered the graduate school at Purdue University, West Lafayette. He obtained his Masters of Science in 2012 from Purdue University and continued to Doctor of Philosophy. During his masters and Ph.D. Uditha Sudheera Navaratne worked as research assistance and teaching assistance in school of engineering technology, Purdue University. In final year of his Ph.D. he joined Purdue University, Northwest as a visiting Instructor.

PUBLICATIONS

PUBLICATIONS

Navaratne, U. S., Kulatunga, N. A., Redmond, M., & Sampaio, D. B. J.(2015). Automated data collection system for performance analysis of home appliances under Conservation Voltage Reduction (CVR). *XI Latin-American Congress Electricity Generation and Transmission*

Fathizadeh M., Navaratne U.S. (2016). Effect of Electrical Alternative Energy Sources on Power Grid Effect of Electrical Alternative Energy Sources on Power Grid. 2016 ASEE Annual Conference & Exposition

Navaratne U.S., Kulatunga N.A. (2016). Smart Grid Emulator with a Hardware in-Loop Smart-Meter Infrastructure. Manuscript submitted for publication.

Navaratne U.S., Kulatunga N.A. (2016). Multi Agent System framework for Distributed Energy Resource Planning. Manuscript submitted for publication.

Navaratne U.S., Kulatunga N.A. (2016). Estrela Da Ilha, Brazil Power System Modelling for Power Quality Analysis and Renewable Energy Integration Studies. Manuscript submitted for publication.s